THE EFFECT OF HEAT TREATING VARIABLES ON TOUGHNESS OF CAST STEELS AND CAST ARMOR

FINAL REPORT OF PART I

ON

CONTRACT DA-33-019-ORD-1510

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Prepared by

STEEL FOUNDERS' SOCIETY OF AMERICA

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June, 1958

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Final Report of Part I on Contract DA-33-019-ORD-1510

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OUTLINE OF THE PROBLEM

The objective of this investigation was to explore variations in the methods and procedures of the heat treatment of cast steels, especially low-alloy cast-armor steels, to ascertain means of further improving the toughness of these steels as measured by low temperature notched-bar impact properties.

It is known that variations in the toughness of cast steel can result through the method of steelmaking such as when phosphorus, sulfur, hydrogen or nitrogen are maintained on the high side, or if the deoxidation treatments produce undesirable inclusion types or distribution. These circumstances produce pronounced changes in the toughness of the steel and usually are easily recognized.

It is further known that the toughness of any particular cast steel can be varied by the heat treatment employed. Water quenching followed by high temperature tempering treatment is most conducive to high toughness values. Also, toughness may be improved by careful attention to the processing methods used in heat treating.

Steel casting heat treatment often consists of many steps: homogenization austenitizing, tempering and stress relieving. Many of these treatments are for relatively long periods of time and often at elevated temperatures. The importance of these heat treatments as they affected the mechanical properties of the steel were ascertained with the considered possibility of shortening these times and reducing the number of operations consistent with maintaining high toughness values.

The research was planned in nine phases employing six different cast steels of increasing hardenability. The cast steel test blocks were taken from production heats, and the heat treatments and testing were conducted at steel foundries.

SUMMARY OF CONCLUSIONS

Twenty-eight conclusions and 10 recommendations have been prepared as the result of these research studies. However, these conclusions can be summarized, as to major findings, as follows:

1—Increasing the temperature or heating time of homogenization (normalizing) does not improve the impact or tensile properties of carbon or low-alloy cast steels.

2—The impact properties of many cast steels are not improved by employing a homogenization (normalizing) treatment prior to quenching.

3—There is no advantage in toughness or tensile properties by heating to a high temperature or a prolonged time prior to quenching.

4—Increasing the tempering time at any tempering temperature will result in a reduction in the hardness of the steel and an increase in toughness.

5—Time of holding after the castings reach the tempering temperature can be very short. A period of 15 to 30 minutes is sufficient. The time is not dependent on the thickness of the section being tempered.

6—The tempering time and temperature of cast steels can be varied to produce a constant hardness. If this is done there is no drop in hardness nor increase in toughness properties as the tempering time increases.

7—Short time tempering of quenched low-alloy cast steels produces toughness equal to or greater than long tempering times, provided hardness values are constant.

8—Changes in section thickness from 1 to 6 inches do not adversely affect the use of the short time tempering treatment.

9—The toughness of cast steels is not improved by a double quench treatment nor a double tempering treatment.

PREFACE

to the

RESEARCH REPORT

The requirements of heat treatment of steel castings were specified many years ago—at least 40 years—when casting customers proceeded to prepare process specifications requiring the heating of castings at the specified heat treating temperatures for one hour per inch of thickness.

There may have been some justification for the establishment of the 1-hour-per-inch requirement back in the early days because records indicate that foundries shipped castings without any heat treatment unless such treatment was specified. Furthermore, heat treating furnaces were not too efficient because many foundries built their own without the advantage of having heat transfer information. The rule of 1-hour-per-inch of maximum section for heat treatment proved satisfactory because most furnace loads would contain castings having at least some section that would be 3 or 4 inches or much greater. The application of this rule resulted in heating periods of a minimum of 4 hours and in many cases foundries were on 8-hour heating cycles.

During the 1930's there was a series of articles published on the advantages of using high temperatures of 1800 degrees F and above for heat treating with the idea of migration of the constituents of the steel so as to result in better casting properties. These treatments became known as homogenization treatments, and heating times even exceeding the 1-hour-per-inch rule were employed.

Much of the cast armor produced in World War II, at least during the early years, was given high temperature homogenization for long periods of time. In fact, armor sections of 2½ inches were held at temperatures of 1700 to 2000 degrees F for as much as 10 hours.

The early rule of 1-hour-per-inch, through long usage, became a law; a sacred law if not a fundamental one, which defied change in customers' specifications.

The rule or law has no basis of fact in this day of well constructed heat treating furnaces and manufacturing procedures which always specify heat treatment as a part of the production procedure of making steel castings.

Heat treatment became a bottleneck in casting production during the period of the Korean affair because so many steel castings were being produced for the military and properties desired could be obtained only through water quenching. The high homogenization temperatures were dropped, holding times were shortened and excellent mechanical and ballistic properties were obtained.

Discussions on these achievements were of great interest in the meetings of the Ordnance Department's Metallurgical Advisory Committee on Cast Armor. It was mainly to answer questions that were raised in these meetings and the desire of the technical people of the Ordnance Department to shorten heat treatments and improve toughness properties of cast armor that these studies were initiated by Watertown Arsenal.

The studies of this research show a new concept in the heat treating of steel castings, namely, the short time heat treatment without prior homogenizing heat treatments.

It is the hope of the Technical Research Committee that after the information of this report is available to the purchaser of steel castings, the 1-hour-per-inch rule will be discarded from specifications and that the procedures of heat treatment will be of interest only to the foundry as just another feature of the foundry's procedure for quality control of its product.

The Technical Research Committee wishes to express its appreciation to the managements of National Malleable and Steel Castings Company and Pacific Car and Foundry Company for offering their facilities for the heat treatment, machining and testing of the cast steels. Numerous tests were made and the problem of identification and correlation of effort was a most difficult one. Special appreciation is given by the Committee to Mr. Herbert A. Conyne, Chief Metallurgist, Pacific Car and Foundry Company and his staff for work well done. Also, the Committe wishes to indicate its appreciation of the tremendous assistance given to the project by the late Harold H. Johnson who was Director of Research, National Malleable and Steel Castings Company, and his able staff. The Committee, likewise, acknowledges with appreciation the research of the Steel Castings Institute of Canada for producing the carbon steels and carrying on the heat treatment studies for the Society. The joint effort was a most satisfactory one.

The Committee also wishes to thank the members of the staffs of the five member companies that produced the production heats of cast steels and cast the necessary test blocks required by the program. They cooperated to the maximum and fulfilled all requirements. Their acceptance of the assignment and their support and interest in the research is greatly appreciated. The contributing companies are as follows:

- Blaw-Knox Company, Foundry & Mill Machinery Division, East Chicago Works, and Union Steel Castings Works
- General Steel Castings Corporation
- Pacific Car and Foundry Company
- Symington Wayne Corporation
- Wehr Steel Company

The Society expresses gratitude to Watertown Arsenal for initiating the studies and providing the necessary funds. Their confidence in the Society's research activities is appreciated. Special acknowledgment is made to Mr. Paul V. Riffin of the Arsenal Metallurgical Staff for his coordinating activities and sound advice.

It should be indicated for the record that funds for the carbon steel and the manganese-boron steel studies were provided by the Steel Castings Institute of Canada and the Steel Founders' Society of America.

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Technical and Research Director

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REPORT ON

RESEARCH PROJECT NO. 42

THE EFFECT OF HEAT TREATMENT VARIABLES ON THE TOUGHNESS OF CAST STEELS

by

Charles W. Briggs

Steel Founders' Society of America

UNDER TERMS OF CONTRACT

between

Ordnance Department USA, Contract DA 33-019-ORD-1510

AND

Steel Founders' Society of America

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THE EFFECT OF HEAT TREATMENT VARIABLES ON THE TOUGHNESS OF CAST STEELS

Introduction

The term "toughness" as related to steel has been used and explained in a number of ways. It can be defined as the property of absorbing considerable energy before fracture, usually represented by the area under a stress-strain curve, and, therefore, involving both ductility and strength.

Formulas expressing toughness have been devised, based on tensile strength and ductility values. However, it is recognized that a test specimen containing a notch will give precise information regarding the nature of brittle fracture of a metal. There are a number of tests for toughness employing a notch, including procedures such as applying a bending or axial tensile load as slowly as in the standard tension test to those of high speed impacts as developed by explosive loading. But increasing the rate of load application only increases the temperature of transition from ductile to brittle fracture. Therefore, the temperature at which the notched test is conducted is most important. A steel is tough or brittle depending on the transition temperature from ductile to brittle fracture.

Most authorities agree that the notched bar impact properties of the steel at low temperature are the best criterion. Regardless of the method used to determine toughness, there must be an arbitrary scale if toughness is to be treated quantitatively. Materials having test values above the arbitrary minimum are regarded as tough. The minimum value apparently moves up and down the scale, depending on strength, hardness, composition, steelmaking and heat treating variables of the steel and the temperature of test.

Low-alloy cast steels, as a class, generally have been considered to be tough. The carbon content of such steels has been maintained usually within the range 0.25 to 0.45 percent and the strength and hardness have been maintained at a high level through heat treatment (100,000 to 200,000 psi).

It is known that a loss in toughness occurs in cast steels if the sulfur and phosphorus contents are maintained on the high side, or if the deoxidation treatments produce undesirable inclusion distributions. These circumstances produce pronounced changes in the toughness of the steel and usually are easily recognized.

A low alloy cast steel may be tested and proved to have excellent toughness, yet the same steel may be made by the same producer or by another foundry, and this steel would exhibit low toughness properties. Such is the case of one of the steels of this study.

The steels appear to be much the same chemically, but, in one case, grain boundry segregation is responsible for low toughness values. The procedure of deoxidation and the products resulting therefrom are the reasons for the low toughness values of this steel.

The toughness of steel can be varied by the heat treatment employed. A martensitic structure resulting from quenching is extremely hard and strong, but steel parts with martensitic structures have low toughness since they can neither undergo plastic deformation nor resist sudden applications of load.

A problem of heat treating consists of imparting toughness to hard and strong quenched steel in order to obtain the most desirable combination of mechanical properties. The solution of the problem requires that the steel be reheated (tempered) below the lower critical temperature. Tempering improves toughness while decreasing strength and hardness. However, the toughness of different steels can be profitably compared only when the hardness of all of them is the same. Most low-alloy steels of different chemical compositions have approximately equal yield and tensile strengths if they possess the same hardness, but they may or may not have the same toughness.

The details of the heat treating procedure may be responsible for variations in the toughness of cast steel, such as: the temperature employed, the length of time at temperature and the character and degree of the quench. The variables are many if it is considered that both the heating cycle before the quench and the tempering cycle following the quench influence the toughness results.

Recent exploratory studies have indicated that short time heat treatments are beneficial to the improvement of toughness of cast steels. Such possibilities have been carefully checked in this research because, even if the toughness was not improved by short time heat treatments, there was the distinct possibility that they would not be deteriorated, thereby reducing heat treating schedules and heat treating costs.

The objective of this investigation, therefore, was to explore the variation in the methods and procedures of the heat treatment of cast steels so as to ascertain means of further improving the toughness of these steels.

SECTION I

RESEARCH PROCEDURES

Cast Steels

The composition of the steels investigated in this research are listed in Table 1.

The reasons for the selection of these steels were: (1) a large quantity of carbon steel is produced and it is a good reference point; (2) the Mn-B steel is a low-alloy non-strategic alloy composition of higher hardenability than carbon steel but lower than many of the low-alloy steels; (3) the Mn-Cr-Mo and Ni-Cr-Mo steels are very useful in section sizes up to about 3 inches; (4) the Mn-Ni-Cr-Mo, a four-way alloy steel, and the Cr-Mo of high chromium content, have hardenabilities that permit their use in heavy sections, possibly as thick as 6-inch sections. In addition these latter steels are widely used for making castings for the Ordnance Corps.

The steels of Table 1 were produced by member companies of Steel Founders' Society and Steel Castings Institute of Canada. The composition of the steels furnished for test purposes is given in Table 2.

More than one heat was necessary, in certain cases, to produce the quantity of test castings needed for the program, such as, carbon steels Nos. 1 and 2, Mn-Ni-Cr-Mo steels Nos. 1, 2 and 3; Cr-Mo steels Nos. 1 and 2. The Mn-Ni-Cr-Mo steel No. 4 and Mn-Cr-Mo steel No. 2 were produced by different foundries than those producing Mn-Ni-Cr-Mo steels Nos. 1, 2 and 3 and Mn-Cr-Mo steel No. 1.

Test Castings

Several types of test castings were employed in this research. The reason for this was that heat treatment studies were to be undertaken on castings of varying section thicknesses. The test castings produced with the steels listed in Table 2 were of the general dimensions shown in Table 3 and illustrated in Figures 1, 2, 3, 4, 5 and 6.

Foundry Preparation of Castings

The test castings were produced by the foundries from steel prepared for production castings. All operations of producing the molds and the castings were carried on as commercial requirements.

The test castings were cooled in the mold, removed and pressure blasted. Gates and risers were removed either by torch cutting or sawing. The test coupons were stamped for identification purposes and shipped to the research agency without heat treatment.

Research Agencies

The heat treating research was carried on at three laboratories engaged on the following steels:

National Malleable & Steel Castings Co.	Mn-Ni-Cr-Mo, Cr-Mo, Ni-Cr-Mo, Mn-Cr-Mo
Pacific Car and Foundry Company	Mn-B, Mn-Cr-Mo
Steel Castings Institute of Canada	C

The research undertaken by the Steel Castings Institute of Canada was carried on in the laboratories of the Department of Mines and Technical Surveys, Government of Canada, Ottawa, Canada.

Each agency was responsible for the machining of test specimens, heat treating operations, testing and test results.

Machining of Specimens

The Arsenal keel casting was heat treated according to the research plans and then sectioned as shown in Figure 1. In some cases the full length test casting was cut in half but if this was done, test specimens were not taken closer than 2 inches

TABLE 1

Composition Ranges of Steels Studied

Class	Type	PERCENT C	Mn	Ni	Cr	Mo
C	AE	0.25 - 0.30	0.60 - 0.90			
Mn-B	AE	0.25 - 0.30	1.30 - 1.50	(B 0.0045 added)		
Mn-Cr-Mo #1	BE	0.25 - 0.30	1.30 - 1.50	-	0.40 - 0.60	0.40 - 0.60
Mn-Cr-Mo #2	BE	0.25 - 0.30	1.30 - 1.50	-	0.60 - 0.90	0.40 - 0.60
Mn-Ni-Cr-Mo	AOH	0.25 - 0.30	1.00 - 1.30	0.75 - 1.25	0.75 - 1.25	0.40 - 0.60
Cr-Mo	BOH	0.25 - 0.30	0.60 - 0.90	-	2.25 - 3.00	0.40 - 0.60
Ni-Cr-Mo	AE	0.25 - 0.30	0.70 - 1.00	0.60 - 0.90	0.60 - 0.90	0.35 - 0.55

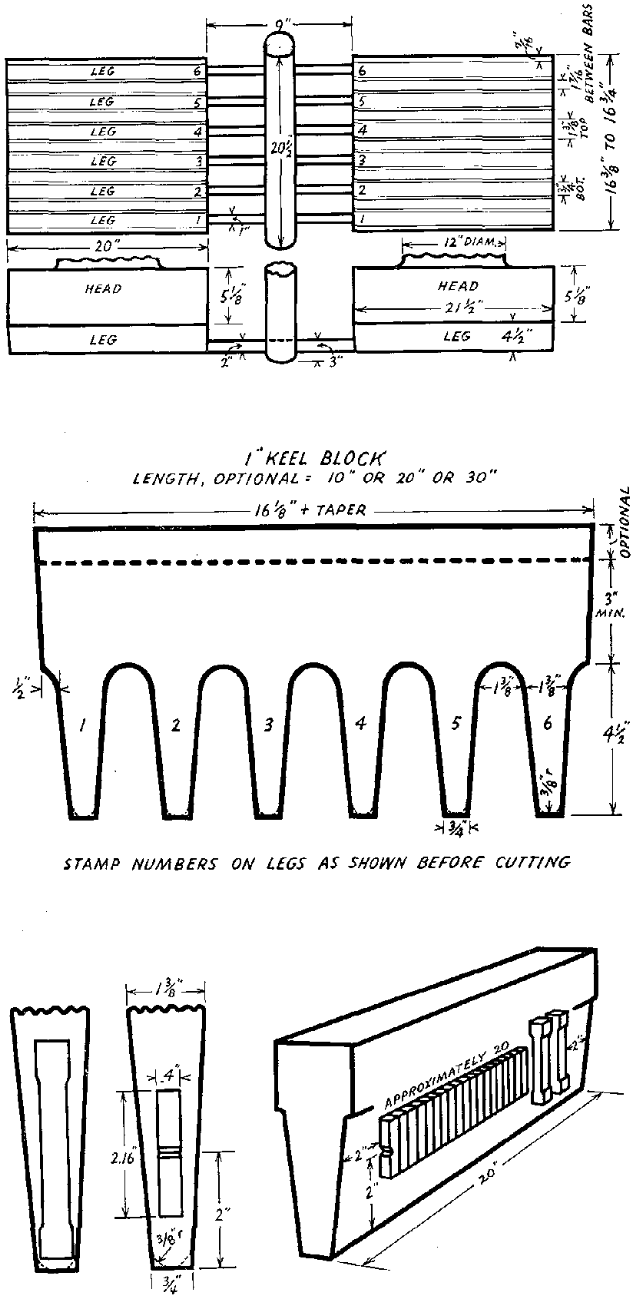


Figure 1—Watertown Arsenal design of 1-inch thick keel casting and method of casting

Design for Double Keel Block Coupon

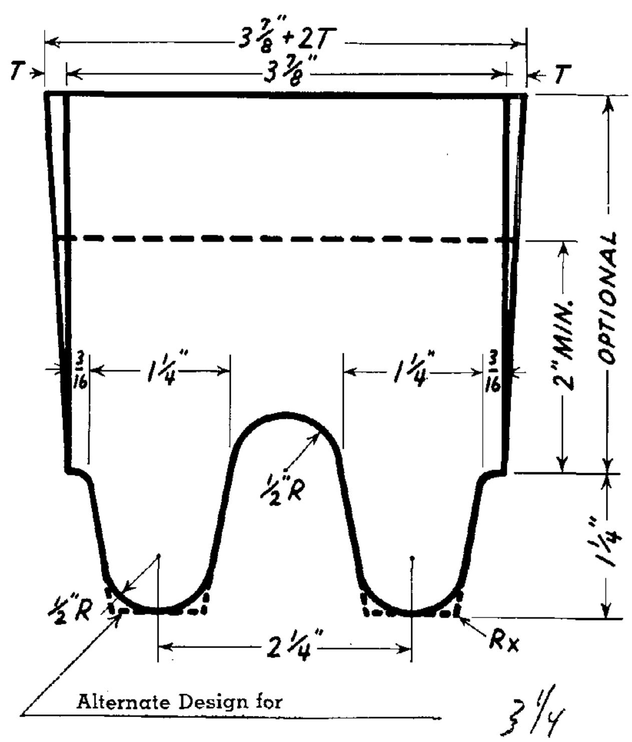


Figure 2—ASTM-A370 1-inch thick keel coupon design

TABLE 2

Analyses of Cast Steels

Class	C	Mn	Ni	Cr	Mo	Si	P	S
C - #1	.28	.71	.07	.08	.01	.45	.027	.023
C - #2	.30	.82	.06	.06	.02	.49	.022	.023
Mn-B	.30	1.51	.07	.12	.03	.38	.037	.049
Mn-Cr-Mo #1	.27	1.41	.28	.59	.57	.38	.012	.011
Mn-Cr-Mo #2	.30	1.47	—	.72	.48	.55	.020	.020
Mn-Ni-Cr-Mo #1	.25	1.49	1.02	.99	.47	.40	.038	.040
Mn-Ni-Cr-Mo #2	.28	1.52	1.14	.95	.53	.34	.036	.030
Mn-Ni-Cr-Mo #3	.26	1.29	1.13	.70	.48	.31	.036	.028
Mn-Ni-Cr-Mo #4	.32	1.20	.87	1.00	.47	.45	.027	.028
Cr-Mo #1	.29	.62	.19	2.49	.54	.40	.017	.016
Cr-Mo #2	.31	.60	—	2.31	.56	.42	.016	.015
Ni-Cr-Mo	.30	.96	.76	.77	.43	.49	.019	.031

TABLE 3

Type and Size of Test Castings

Type	Size, inches	Steels produced in each section size	Reference Figure
Arsenal Keel	1 x 4 x 20	Mn-Ni-Cr-Mo, Cr-Mo, Mn-B, Mn-Cr-Mo, Mn-Cr-Mo #2, Ni-Cr-Mo	1
ASTM Keel	1 x 1-1/4 x 8	C, Mn-Cr-Mo #2	2
Blaw-Knox Keel	1-3/4 x 2-3/4 x 12	Mn-Ni-Cr-Mo #4, Mn-Cr-Mo #2, Ni-Cr-Mo	3
3 in. Blocks	3 x 9 x 12	C, Mn-B, Mn-Cr-Mo, Mn-Ni-Cr-Mo, Cr-Mo	4, 6
6 in. Blocks	6 x 14 x 14	Mn-Ni-Cr-Mo, Cr-Mo	5, 6

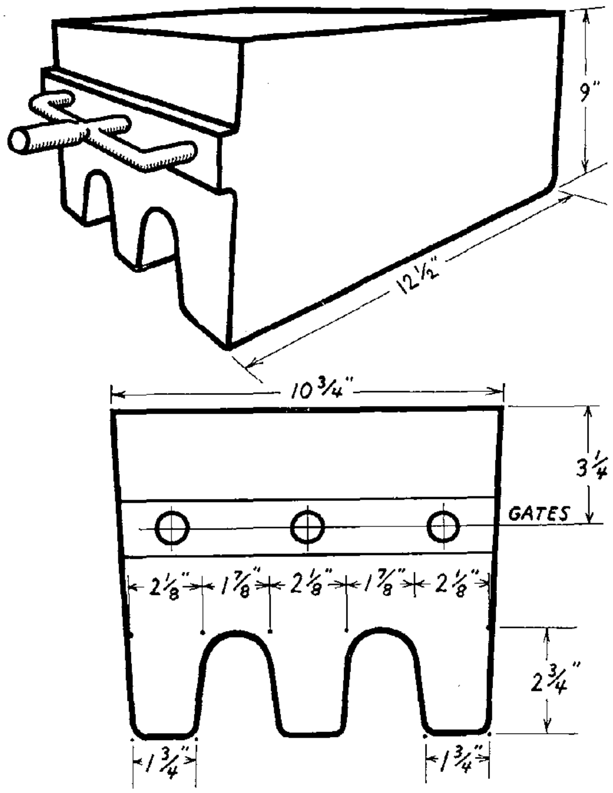


Figure 3—Blaw-Knox test block design

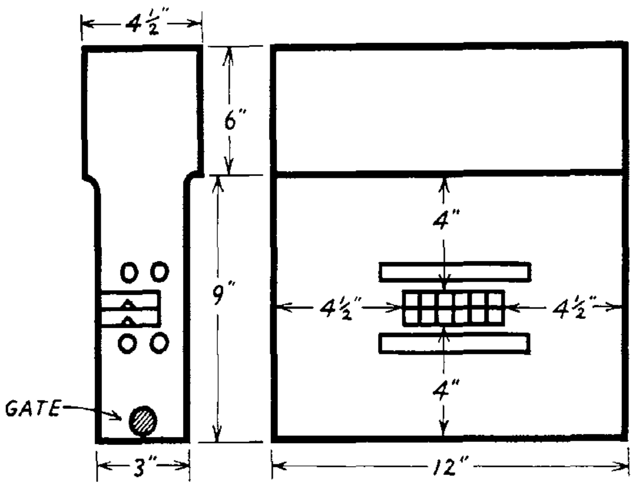


Figure 4—3-inch test block design

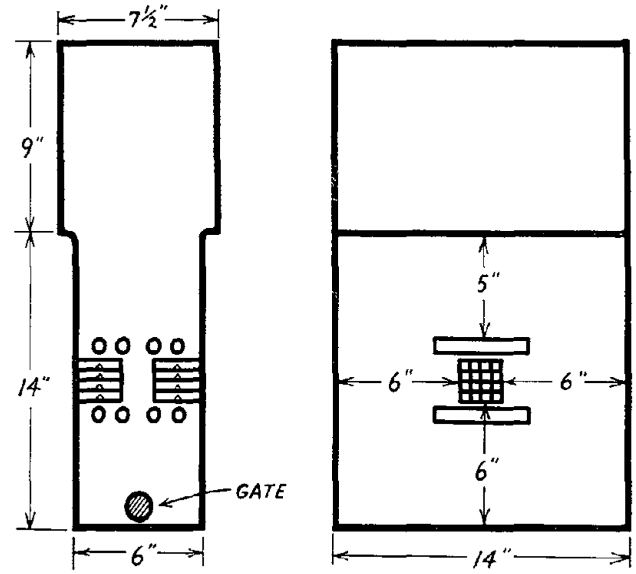
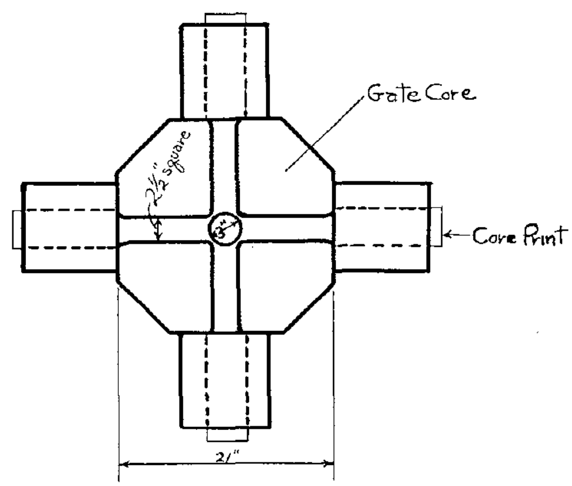
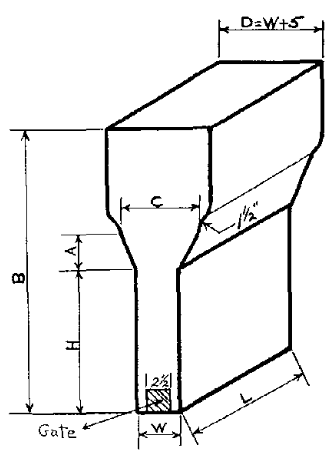


Figure 5—6-inch test block design





PATTERN DIMENSIONS

	A	B	C	D	L	H	W
6"	3	29	8¼	11⅛	14¼	15	6⅛
3"	2¾	20½	5½	8⅛	9 5/16	10⅜	3⅛

Figure 6—Method of casting production of the 3- and 6-inch test block designs

from the casting end faces. Leg numbers 1 and 6 were cut off, marked and held and most all test work was done on legs 2, 3, 4 and 5. This was done because of possible differences in freezing rate of the outside legs and the effect that this condition may have on uniformity of impact values.

Impact and tensile specimens were machined from the 1 x 1¼ inch legs of the ASTM keel after heat treating operations.

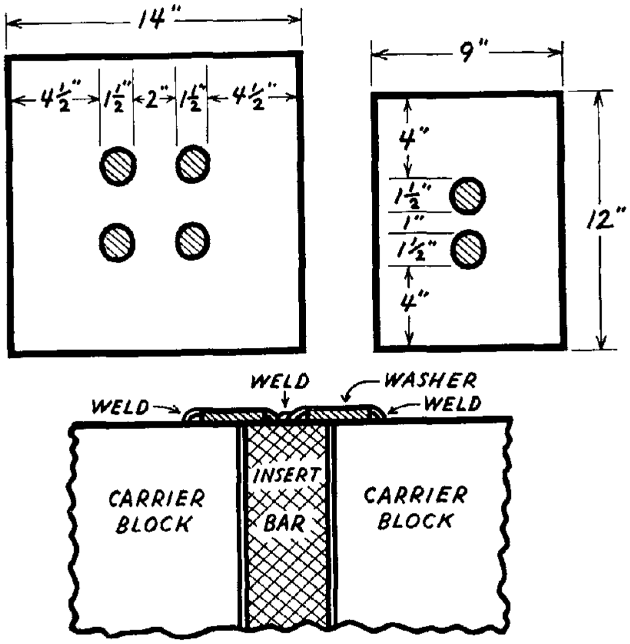


Figure 7—Details of spacing and welding of insert-bar in the carrier blocks

The Blaw-Knox keel with 1¾-inch thick section was employed to machine 1½-inch diameter insert-bars from the legs prior to heat treatment. The insert-bars were then placed in a center-drilled hole in the 3 x 9 x 12- and 6 x 14 x 14-inch carrier blocks for heat treatment. After heat treating operations were complete the insert-bar was removed from the carrier block and machined into impact and tensile specimens. That portion of the insert-bar adjoining the cooling face of the carrier block was discarded in accordance with the requirements of Figures 4 and 5.

In many cases the research agencies did not employ insert-bars in carrier blocks. They heat treated the 3-inch and 6-inch blocks and then sectioned them in accordance with the sketches of Figures 4 and 5. One research agency, in a number of cases, sectioned the 3- and 6-inch blocks prior to heat treatment, and machined insert-bars for carrier blocks. Then, after the complete heat treating operations, the insert-bar was removed and machined into impact or tensile specimens.

The standard 0.505-inch tensile specimen with 2-inch gage length was machined for tensile testing. Charpy V-notch impact specimens were the standard 0.394-inch bars machined according to requirements specified by Watertown Arsenal.

The insert-bars were machined to 1½ inches in diameter to permit obtaining four Charpy specimens from the cross section. Saw cuts of ⅛ inch thickness split the insert-bar into the four specimens which could be roughed out to 0.450 inches square.

An insert-bar machined from a 3-inch block will yield four Charpy specimens, while one cut from a 6-inch block will produce eight Charpy specimens.

The spacing of the insert-bars in the 3- and 6-inch carrier blocks was standardized as illustrated in the sketch, Figure 7. The insert-bar was sealed into the carrier block by welding a 2-inch diameter steel washer on the block faces as shown in Figure 7. These procedures were approved by Watertown Arsenal.

Every effort was made to machine the impact bar with parallel faces and standard notches. A technique worked out by Watertown Arsenal was used. The notches were prepared on a horizontal milling machine using a carbide fly cutter. All notches were measured on a micro-projector so that only those prepared to the standard notch profile were employed for test purposes.

Heat Treating Methods

Heat treating was carried on in the research agencies with the following equipment:

National Malleable & Steel Castings Company . . . A commercial heat treating furnace to hold 5 tons of castings was employed. The furnace was gas-fired, had a hearth area of 10 x 12 feet serviced by a gantry crane. Annealing grids only large enough to hold a block were employed. All blocks and keel castings were located close together in the furnace in such a manner that they could be removed from the furnace, one at a time, so that each casting could receive the desired heat treatment.

Pacific Car and Foundry Company . . . Two electric furnaces were employed for the heat treating studies; (1) a Hoskins 13 KW, and (2) a Hevi-Duty 10 KW rated capacity. Neither furnace was provided with forced circulation.

Steel Castings Institute of Canada . . . Austenitizing up to 1850 degrees F was carried on in a Homo Carb furnace rated at 72 KW and tempering in a Homo Draw furnace rated at 40 KW. Treatments at 1950 and 2050 degrees F were made in a Globar muffle furnace. The Homo furnaces were provided with forced circulation to minimize thermal gradients.

General Requirements . . . All installations at the three research agencies were equipped with automatic controllers. Heating and cooling curves were determined using micromax recorders and thermocouples welded to the surface or inserted in the center of individual castings. These curves, which will be referred to later in the report, established the heating and cooling characteristics of the furnace and were employed to determine the time lag occurring between the time at which the furnace reached temperature and the time at which the load reached temperature.

In most cases cold loads were placed in furnaces which were at temperature. Holding times were calculated after the center of the block was at temperature as determined from the heat transfer curves.

Particular care was exercised to eliminate extraneous variables so that individual results for subparts of the research would be comparable with one another.

All quenching was carried on in water with water temperatures between 70 and 90 degrees F at the start of quenching. In some cases the water temperature at the end of quench would be 100 degrees F. Cooling curves for the various heat treatments will give the characteristics of heat transfer.

The term "homogenizing heat treatment" is used in this report to refer to any heat treatment prior to the heating for quenching treatment. Normally the term "homogenization" implies a heat treatment at temperatures above those ordinarily used for normalizing and the term usually implies long holding times. This report covers high temperature heating for long times and also usual temperatures at short times as constituting prior heat treatments. Instead of confusing the reader by interchangeably using the terms homogenization and normalizing, it was decided to refer to all heat treatments that are given prior to the heating for quenching, as homogenizing or homogenization.

Testing Procedures

Standard testing conditions were employed. Impact tests were made on Olsen and Riehle machines. All machines were tested, and in one case modified and retested to produce standard check results. Watertown Arsenal furnished each research agency with a set of 15 machined Charpy specimens produced from a standard steel for which they knew the Charpy values at two different hardness levels and the deviation that was expected to be shown in testing. Values obtained by the research agency were reported to Watertown Arsenal and approval of the machine and testing methods was given after close comparative values were obtained.

Impact tests were made at +70, -40 and -80 degrees F. Special tongs of a Watertown Arsenal design were used for handling the impact specimens to insure specimen alignment in the machine supports. The tongs were cooled with the specimens. Quenched and tempered specimens were tested in triplicate.

Hardness testing was made directly in Brinell or converted to Brinell from Rockwell C testing. Two of the research laboratories took a Rockwell C reading on each face of the impact bar at each end, or 8 readings for each bar, and averaged these readings.

SECTION II
PROPERTIES OF CAST STEELS WITHOUT HEAT TREATMENT

Transformation Temperatures

The critical temperatures of several of the steels employed in the research were determined by the standard dilatometric technique. Heating and cooling rates of 2½, 5 and 15 degrees per minute were employed. Transformation temperatures determined from heating and cooling curves (example given in Figure 8) are summarized in Table 4.

Austenite decomposition during cooling takes place slowly in the alloyed steels. For example, the decomposition in the Cr-Mo steel was not detected until the specimen had cooled to 1445 degrees F, approximately 150 degrees F below the Ac_3 temperature. The Mn-Ni-Cr-Mo steel transforms much more slowly than any of the steels.

The higher heating and cooling rates of 15 degrees per minute resulted in slightly overheating at the Ac_1 temperatures.

Undercooling of austenite at the rate of 15 degrees F/min., and even at the relatively low rate of 5 degrees F/min., precludes the use of cooling curves for the determination of critical temperatures. However, these rates of cooling afford an interesting comparison of the sensitivity of austenite decomposition to cooling rate in these steels. This information is of particular interest in view of the fact that the heat treating studies were concerned with rapidly cooled steels (water quenched).

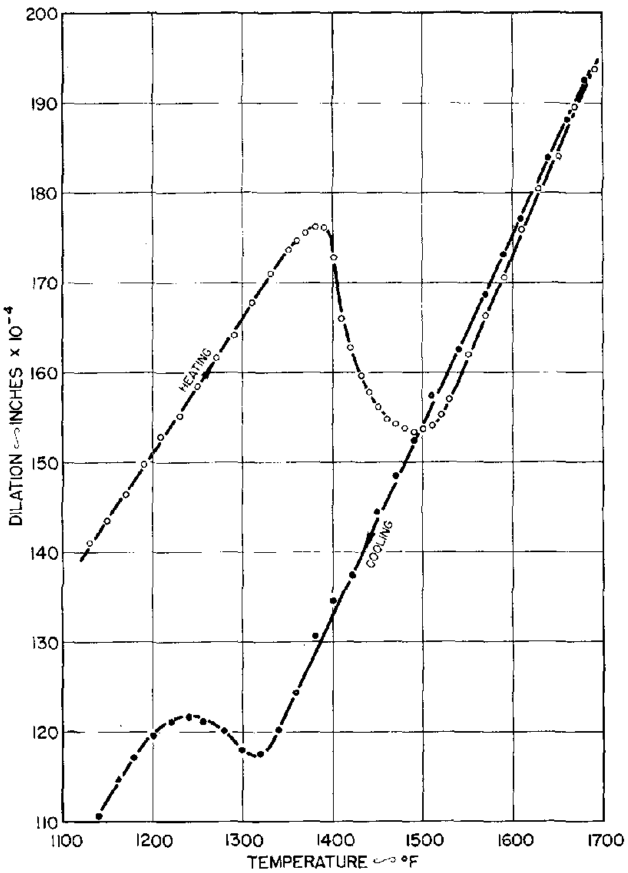


Figure 8—Thermal expansion characteristics of Mn-Cr-Mo steel. Heating and cooling rate 5 degrees F per minute

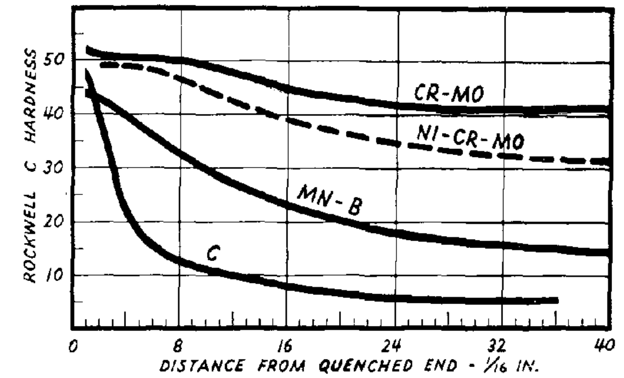


Figure 9—Hardenability curves for C, Mn-B, Ni-Cr-Mo and Cr-Mo cast steels (See Table 2 for steel analyses)

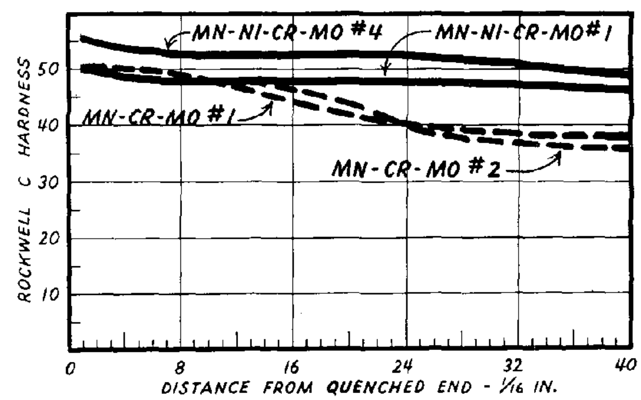


Figure 10—Hardenability curves for Mn-Ni-Cr-Mo and Mn-Cr-Mo cast steels (See Table 2 for steel analyses)

TABLE 4

Critical Transformation Temperatures

Steel Type	Heating-Cooling Rate °F/Min.	Critical Temperatures - °F Ac$_1$	Ac$_3$	Ar$_1$	Ar$_3$
C	2-1/2	1360	1540	1230	1420
Mn-B	5	1360	1530	1160	1325
Mn-B	15	1370	1550	1130	1340
Mn-Cr-Mo	5	1360	1520	1200†	1320
Mn-Cr-Mo	15	1380	1550	‡	‡
Mn-Ni-Cr-Mo	5	1365	1580	‡	‡
Mn-Ni-Cr-Mo	15	1400	1580	‡	‡
Cr-Mo	5	1350	1500	700*	1400
Cr-Mo	15	1360	1500	680*	1340

† Ferrite precipitation continued down to 1200° F where transformation stopped. The remaining austenite did not transform to pearlite when cooling was continued at 5°F/min down to 1000° F. The structure of a specimen after air cooling from 1000°F to room temperature consisted of ferrite and martensite.

‡ No transformation in range 1700 to 1000° F. Structure of a specimen air cooled from 1000°F showed ferrite and martensite.

* A split transformation begins at 1300°F.

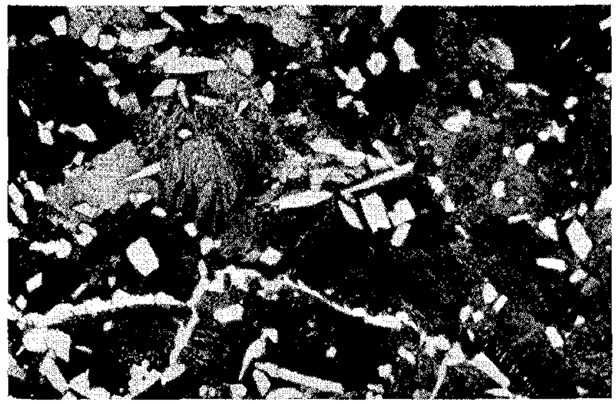
Hardenability

End-quenched hardenability curves were prepared on all the steels employed in the research study. These steels were machined into standard end quench bars and tested according to ASTM procedure. These curves are illustrated in Figures 9 and 10. It will be observed that an excellent spread in hardenabilities was obtained from the steels selected for study. These curves would indicate that the carbon steel is certainly not adaptable to many applications in the quenched and tempered condition. The Mn-B steel apparently would be acceptable in light section castings under one inch. The Mn-Ni-Cr-Mo and the Cr-Mo steels apparently are adaptable to sections of 6 inches and possibly greater, whereas the Mn-Cr-Mo and the Ni-Cr-Mo steels fill a gap of acceptability to 3- to 4-inch sections.

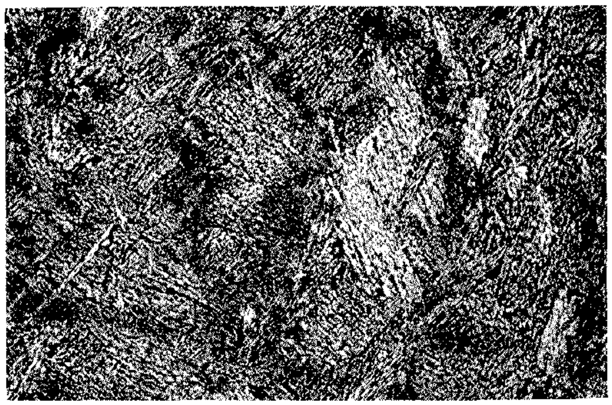
As-Cast Microstructure

The as-cast microstructures of the four cast steels used in all phases of the research are illustrated in Figure 11. The inclusions were predominantly Type III for all steels, examples of which are shown in

11a—Carbon steel, 1-inch section (200X)

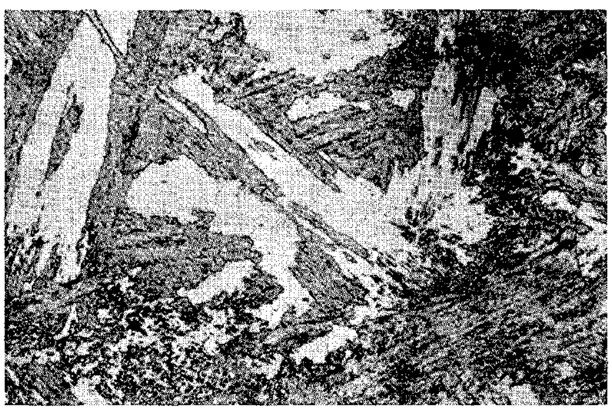


11b—Mn-B steel, 1-inch section



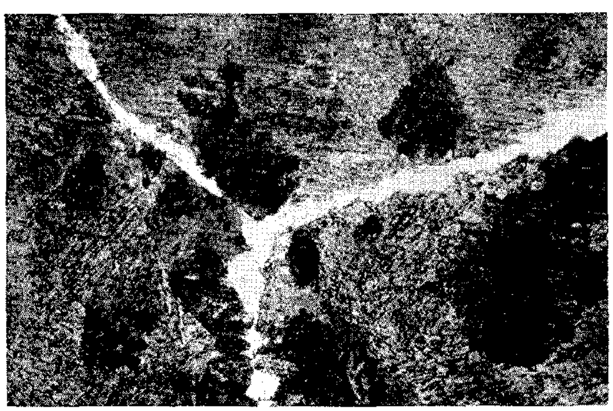
11c—Mn-Cr-Mo steel, 1-inch section

11d—Mn-Cr-Mo steel, 3-inch section

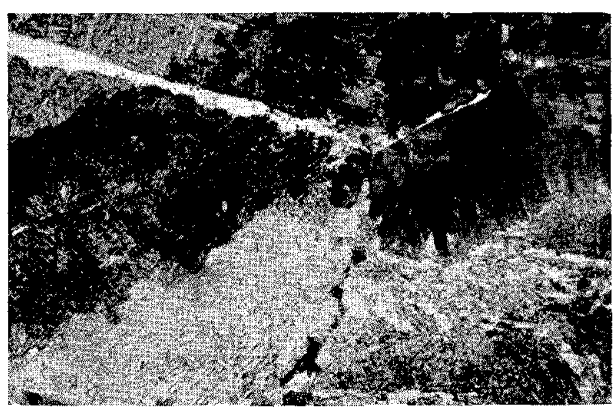


11e—Mn-Ni-Cr-Mo steel, 1-inch section

11f—Mn-Ni-Cr-Mo steel, 6-inch section

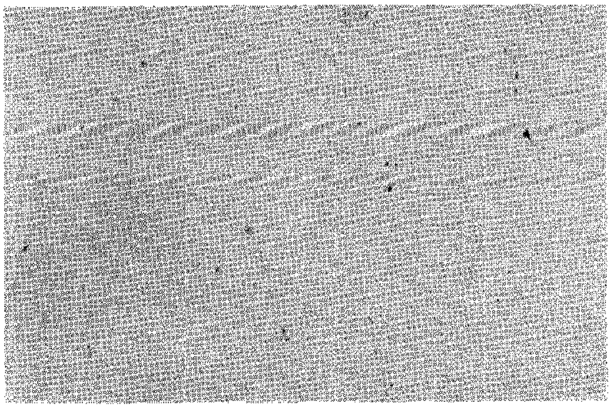


11g—Cr-Mo steel, 1-inch section

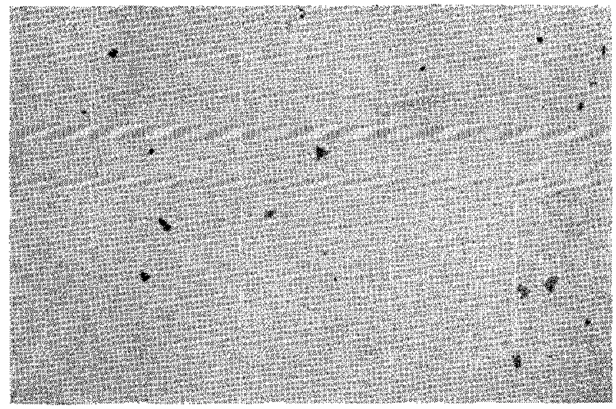


11h—Cr-Mo steel, 6-inch section

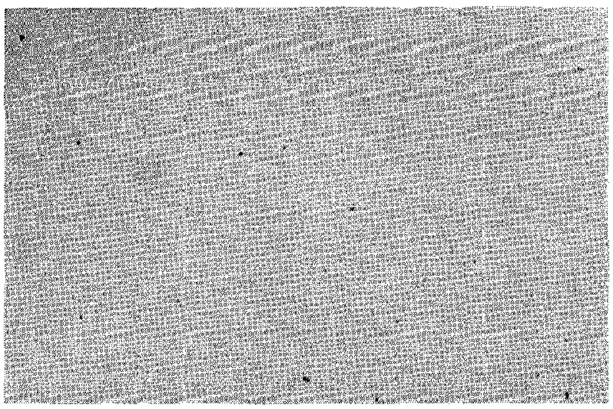
Figure 11—As-cast microstructures 100X Nital etch



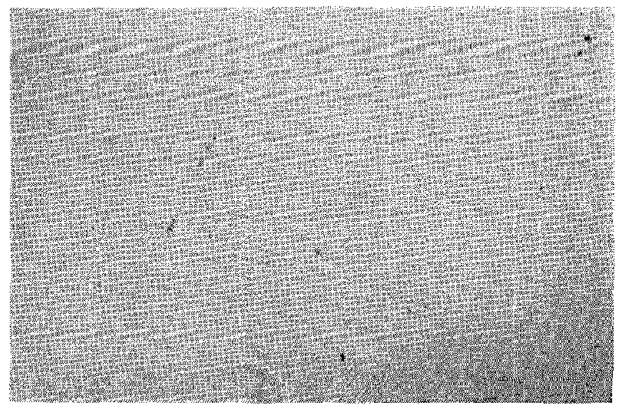
12a—Mn-Ni-Cr-Mo steel 1-inch Section Types III and II



12b—Mn-Ni-Cr-Mo steel 6-inch Section Type III



12c Cr-Mo steel 1-inch Section Type I



12d—Cr-Mo steel 6-inch Section Types I and III

Figure 12—Inclusion distribution 100X unetched

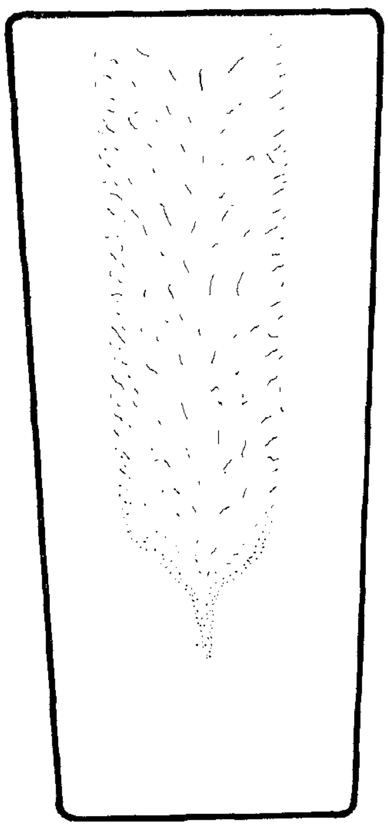


Figure 13—Sketch of segregation disclosed after deep acid etching of the 3-inch block casting. Scale: 1" = 1.7"

Figure 12. The structure types can be listed as follows:

Carbon—random blocky ferrite

Mn-B—grain boundary ferrite plus idiomorphic ferrite and pearlite

Mn-Cr-Mo—fine Widmanstatten ferrite plates

Mn-Ni-Cr-Mo—fine Widmanstatten ferrite plates and acicular products (bainites and martensite)

Cr-Mo—pearlite around grain boundry ferrite

Discontinuities

Slices were prepared from the keel castings and the block castings and X-ray radiographs indicated that the castings were free from shrinkage on the basis of 2 percent sensitivity. Deep acid etching, however, showed some segregation in the 3-inch block as indicated in the sketch of Figure 13. It is difficult to correlate property values to the segregation pattern shown in Figure 13 but in general it was noted that property values for the 1- and 6-inch sections were slightly superior to those of the 3-inch section. It is only problematical that the segregation pattern was responsible for these observed results.

SECTION III
EFFECT OF QUENCHING RATE ON NOTCHED-BAR IMPACT PROPERTIES

One of the variables encountered in these heat treating investigations was the effect of quenching from the austenitizing temperature on the notched-bar impact values. Many tests were performed before the anomalies of the test results at –40 degrees F became convincingly apparent. However, test studies were stopped until the techniques could be reviewed and revised to give the optimum results from a given heat treatment.

The discrepancies occurred mostly for the 3- and 6-inch test block castings with the impact values at –40 degrees F being considerably lower than would be expected.

An interesting correlation of the effect of the quench on hardness and notched-bar impact values was carried out on the Mn-Ni-Cr-Mo No. 4 steel across a 5-inch section. Impact values at –40 degrees F were taken at 1 and 2½ inches from the surface of the 5-inch insert-bar quenched in a 6 x 14 x 14 inch carrier block. The results of these studies are illustrated in Figure 14. The spray quench is a drastic water quench under pressure directed on the casting from various nozzles.

All of the 5-inch sections were tempered to the 241-255 BHN range, yet the impact values varied over a wide range depending on the as-quenched hardness. Air cooling was employed as one of the heat treatments in order to show the maximum range in impact values resulting from vastly different cooling speeds.

It is obvious that when the quench was sufficiently drastic to produce a uniform as-quenched hardness across the specimen at a high hardness level (8 min. spray quench), the impact values near the surface and at the center of the cross section were uniform and they were very high. However, if a short-time spray quench of 5½ minutes was employed, the casting did not quench out cold and the specimen taken at 1 inch below the surface had a hardness of 44 R_c with an impact value of 42 ft. lbs. as compared with 21 ft. lbs. obtained on the specimen taken from the middle of the insert-bar where the as-quenched hardness was 41 R_c. Similarly, impact values for other test specimens, whose as-quenched hardness values were 40 R_c or less, were quite low.

The quenching technique, which had been specified by the investigation, consisted of immersing in rapidly circulating water, the 14 x 14 x 6 inch and the 9 x 9 x 3 inch carrier blocks containing the insert-bars. The blocks were quenched for a predetermined time which would permit sufficient heat in the carrier blocks to equalize at about 300 degrees F. The blocks were removed from the quench tank and transferred rapidly to waiting tempering furnaces.

The importance of the drastic quench for highly alloyed steels such as the Mn-Ni-Cr-Mo steel indicated that the removal of the blocks from the quench at 300 degrees F was not sufficiently drastic and that they should remain in the quench until cold.

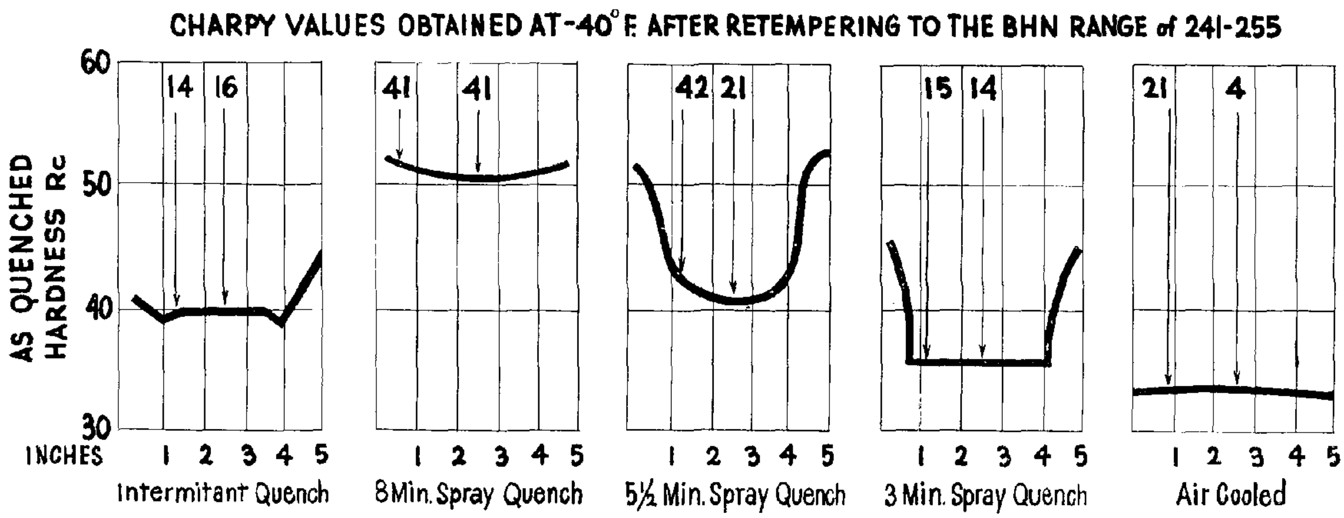


Figure 14—Effect of quenching rate on the hardness and impact values of a 5-inch insert-bar of a Mn-Ni-Cr-Mo steel located in a carrier block

Also, it was decided to check on the production quenching of the Mn-Ni-Cr-Mo and the Cr-Mo steels at the foundries where these steels were produced.

The impact values obtained by the different quenching methods on 6-inch thick blocks of different width and length measurements are summarized in Table 5.

The spray quench is the most drastic quench as is evidenced by the as-quenched hardness values for both steels. Again it is noticeable that when the as-quenched hardness was recorded at 40 R_c or below, the impact values at −40 degrees F dropped off sharply.

The maximum Charpy values obtained by the two steels at −40 degrees F differ somewhat at a constant tempered hardness value. These differences result more from the steelmaking history rather than the alloy composition employed.

Figures 15 and 16 illustrate the as-quenched hardness for 6-inch sections when produced by various quenching operations for two of the alloy steels. Values obtained for the 1- and 3-inch sections on immersion quenching cold, in water, are shown in Figure 17.

The results presented in this section of the report indicated that a quenching practice be employed so as to quench the carrier blocks as rapidly as

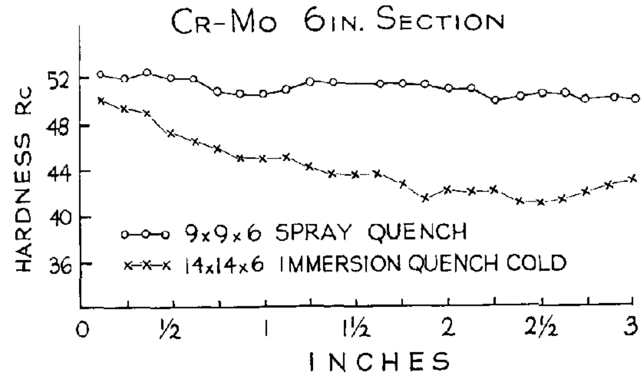


Figure 15—As-quenched hardness survey of Cr-Mo steel insert-bars in carrier blocks of 6-inch section with different severity of water quench

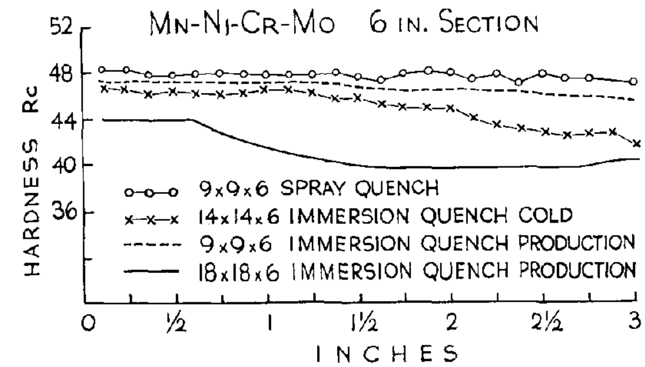


Figure 16—As-quenched hardness survey of Mn-Ni-Cr-Mo steel insert-bars in carrier blocks of 6-inch section with different severity of water quench

TABLE 5

"As-Quenched" Hardness vs. Impact after Tempering

HEAT TREATMENT		HARDNESS		CHARPY-V NOTCH † ft-lbs.	
Insert-bars in Carrier blocks as listed		As-Quenched (R_c at 1")	Tempered (BHN)	70°F	−40°F
Cr-Mo 6 in. Block (inches)	**Cold Quenching by**				
14 x 14 x 6	Immersion	‡	248	62.7	60.3
14 x 14 x 6	Immersion	44	255	67.0	58.0
14 x 14 x 6	Immersion	45	241	67.5	60.0
9 x 9 x 6	Immersion	39	248	60.7	40.2
9 x 9 x 6	Spraying	50	262	64.0	60.3
14 x 14 x 6	Production Quench	46 - 48	269	—	60.7
14 x 14 x 6	Production Quench	46 - 48	203	—	94.0
Mn-Ni-Cr-Mo 6 in Block (inches)					
14 x 14 x 6	Immersion	47	248	46.5	36.2
9 x 9 x 6	Immersion	41	255	50.8	35.0
9 x 9 x 6	Spraying	48	241	51.2	40.0
18 x 18 x 6	Production Quench	40	255	—	28.0
9 x 9 x 6	Production Quench	47	248	—	30.5
9 x 9 x 6	Production Quench	‡	241	—	35.5
9 x 9 x 6	Production Quench	45	235	—	37.5

† Average of 2 or 3 Charpy Tests

‡ Insert-bar not removed from carrier block until after tempering treatment

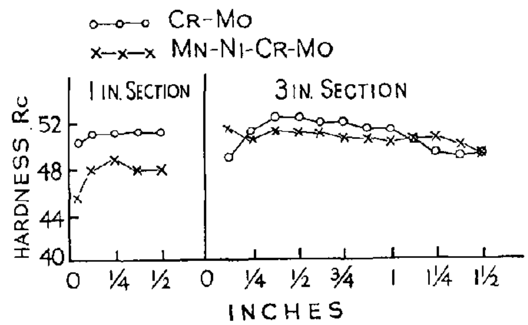


Figure 17—As-quenched hardness of 1- and 3-inch sections of Cr-Mo and Mn-Ni-Cr-Mo steels water immersion quenched cold

possible and to quench them cold instead of removing the blocks from the quench at 300 degrees F. It was decided that the criterion of an acceptable quench would be that the as-quenched hardness of the insert-bar at 1 inch from the surface should be 44 R_c or greater.

Summary of Effect of Quenching Rate

1—The relative severity of the quench results in a variation in notched-bar impact properties.

2—Highest impact properties at −40 degrees F are attainable when the as-quenched hardness of a section 1 inch from the surface is greater than 40 R_c (for 0.25 to 0.30 percent carbon content).

SECTION IV

RELATIONSHIP BETWEEN IMPACT VALUES AND SPECIMEN LOCATION IN THE KEEL TYPE OF TEST CASTINGS

The Research Committee has expressed some concern over the reproducibility of test data and the possible inferior values that are obtained by the impact testing of specimens machined from the 1 x 4 x 20 inch keel castings. In fact, it was stated that the 1¾ x 2¾ x 12 inch keel castings, which are used for insert-bars, produce more consistent and superior impact values.

There was some basis for this concern as was shown by J. E. Black of Detroit Arsenal [1] in published studies regarding the relationship between the type of test block or plate and the impact values produced. Captain Black's studies showed that impact specimens machined across the length of a 1 x 6 x 10 inch vertical keel type casting varied from 28 to 19 ft. lbs. with the middle portion exhibiting the poorest values.

It was decided, therefore, to examine the keel type castings employed in this study so as to ascertain the amount of divergence of impact values in each of the three types of keel test castings.

Procedures and Location of Specimens

The experimental procedures consisted of heat treating in one charge keel castings of the following types and compositions:

Keel Type Castings	Cast Steel
1 x 4 x 10 inches	Mn-Cr-Mo #2, Ni-Cr-Mo, Cr-Mo Mn-Ni-Cr-Mo #1, Mn-Ni-Cr-Mo #4
1-3/4 x 2-3/4 x 12 inches	Mn-Cr-Mo #2, Ni-Cr-Mo, Mn-Ni-Cr-Mo #4
1 x 1-1/4 x 8 inches	Mn-Cr-Mo

The 1 x 4 x 20 inch keels were split in half prior to heat treatment. All castings were given the same heat treatment, although it was recognized that there would be slight differences in the hardness level between keel castings because of the difference in analyses. However, the hardness level throughout each keel would be the same and, therefore, the impact results would be comparable. The heat treatment consisted of the following:

Heat to 1650 degrees F, hold 1½ hours, water quench.

Temper at 1250 degrees F for 2 hours, water quench.

Charpy V-notch impact specimens were machined from each block in the positions noted in Figure 18. These sketches are not drawn to scale but indicate that three specimens were cut vertically from the two outside quarters and one set of three specimens was removed from the middle section of each block. Horizontal specimens were machined from the relative locations shown in the sketches. The impact specimens were cut from the ASTM 1 x 1¼ inch keel along the length of the test piece.

The specimens were machined from the middle of the cross section of the keel leg. The horizontal specimens were notched on the side facing the center of the section. In those instances where the keel casting has been cut into two 10-inch lengths, notation is made as to which end was the cast surface and which the cut surface.

The Charpy impact values obtained in testing and the average hardness of the bars are shown on the sketches of Figure 18. The same data are presented in another form in Figures 19 and 20. In addition,

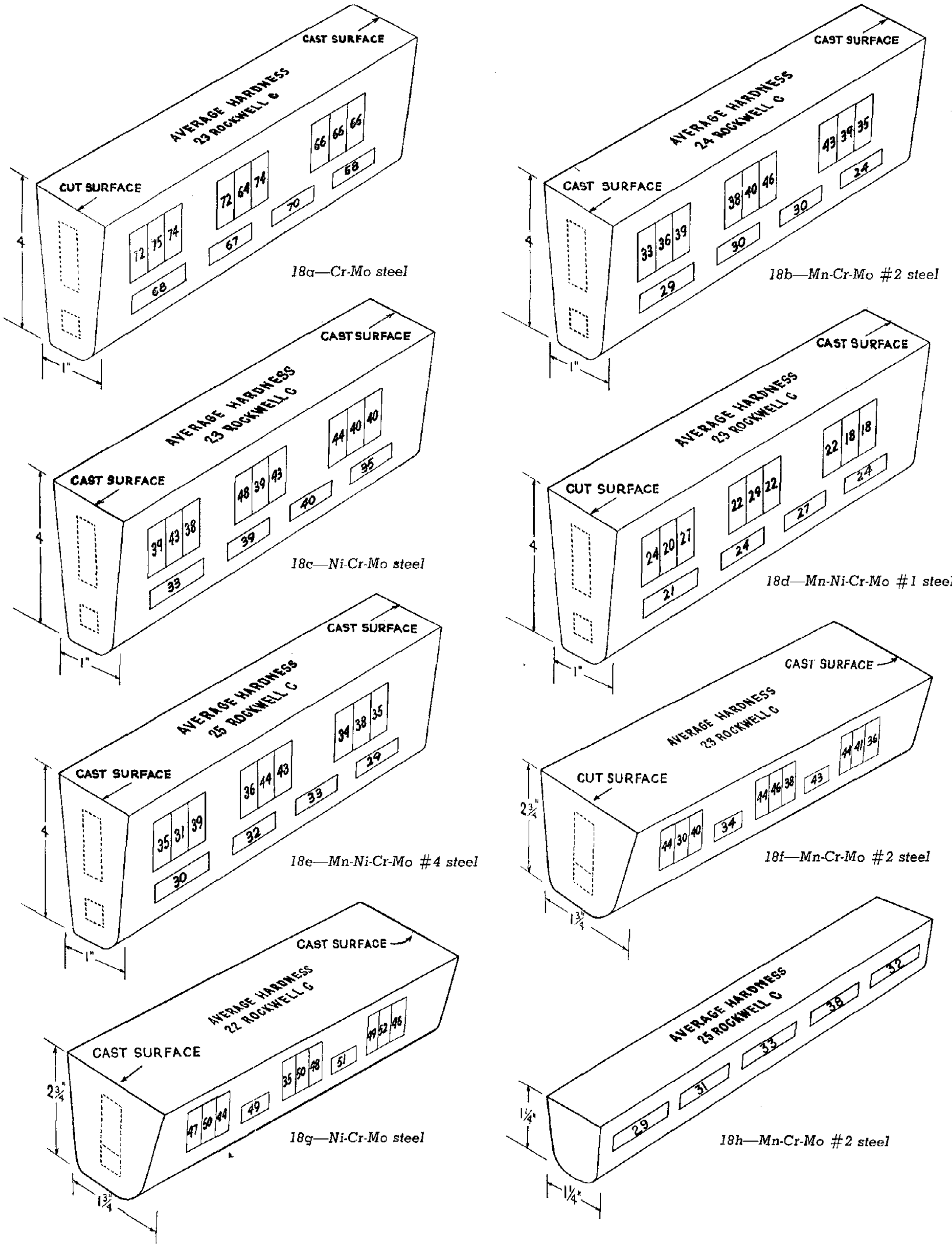


Figure 18—Charpy V-notch impact values at −40 degrees F in keel test castings for various quenched and tempered cast steels

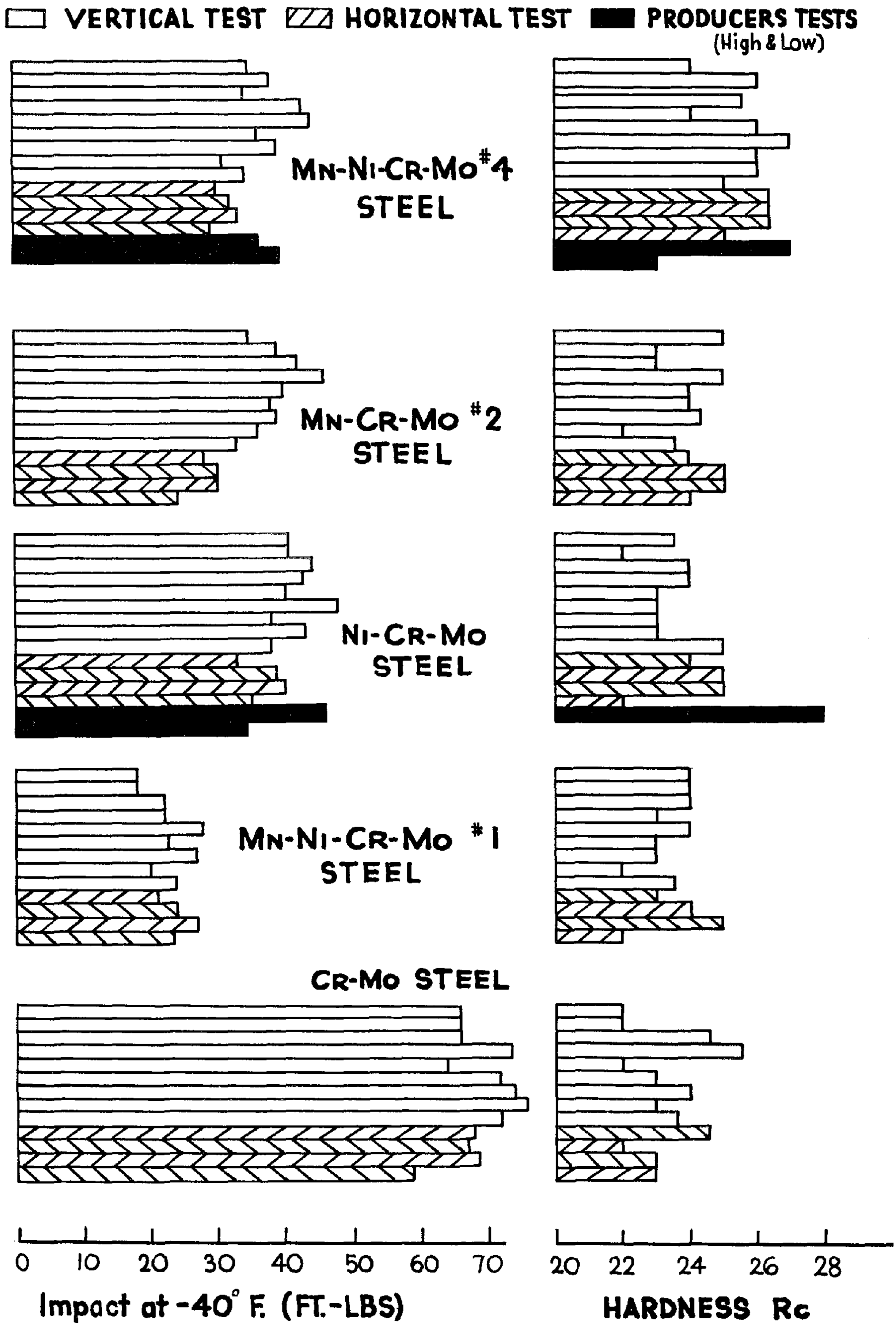


Figure 19—V-notch Charpy values at −40 degrees F for the 1 x 4-inch keel castings after quench and tempering heat treatment

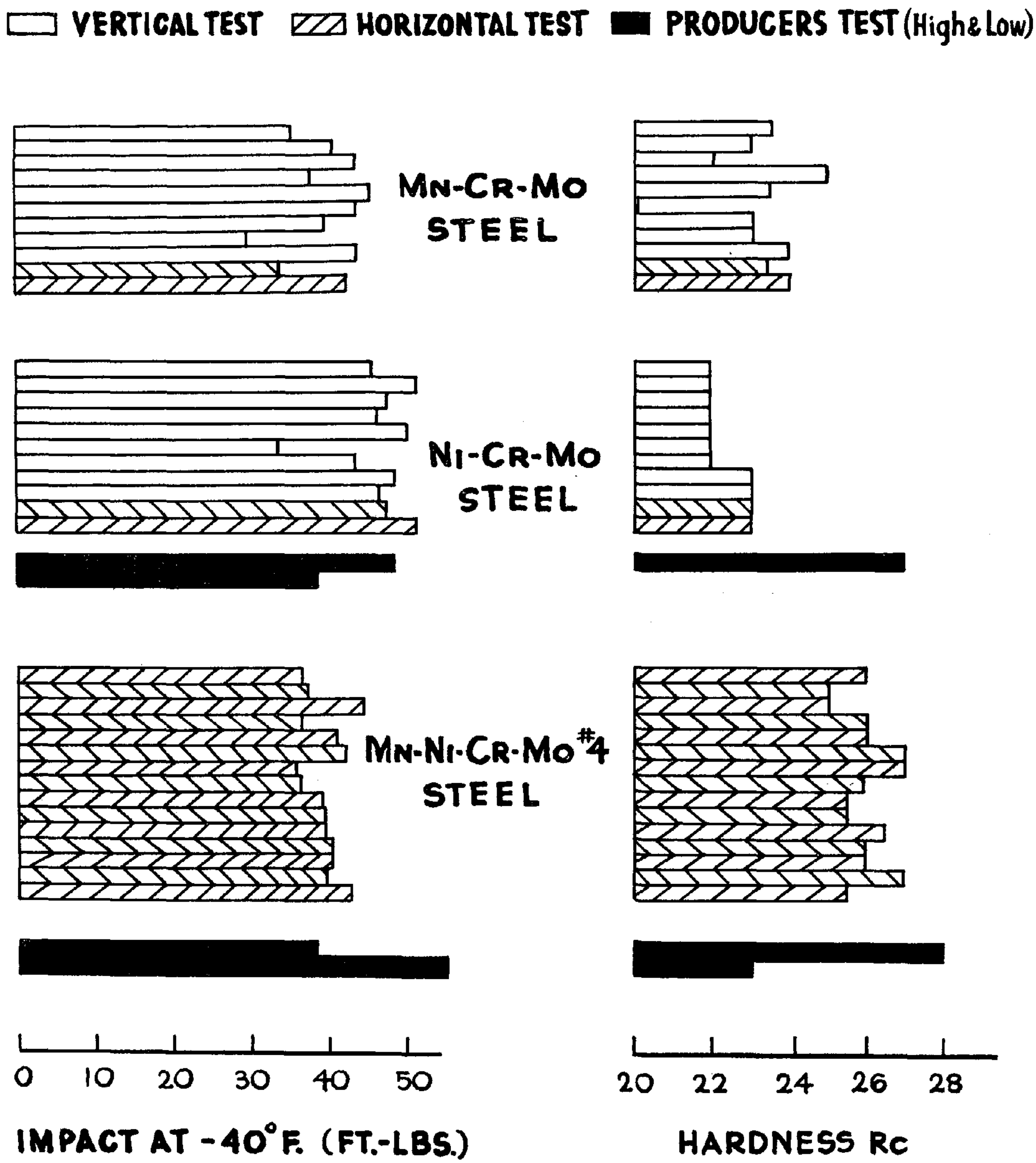
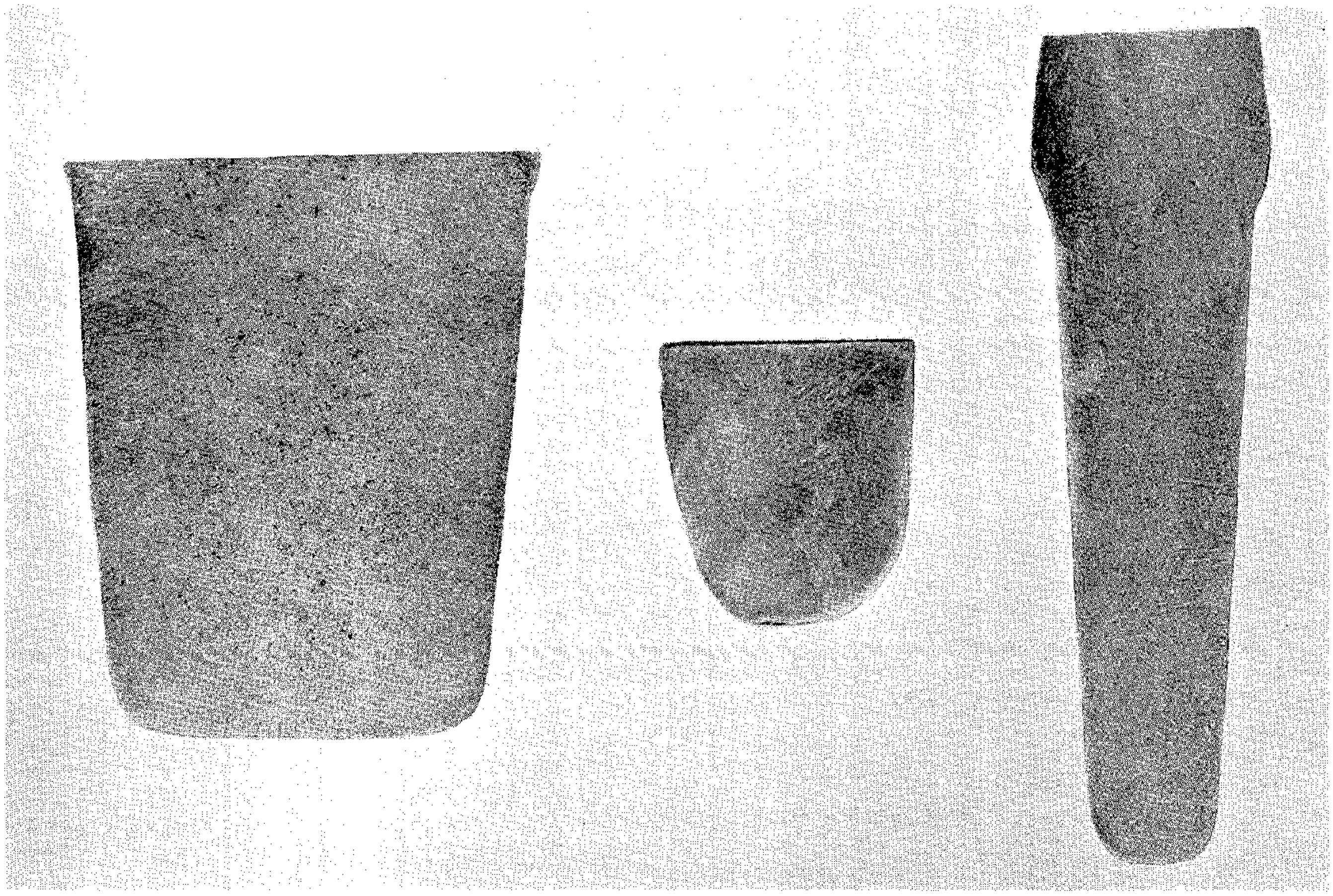


Figure 20—V-notch Charpy values at –40 degrees F for 1-3/4 x 2-3/4 inch keel castings after quench and tempering heat treatment



a. *Blaw-Knox, 1¾ x 2¾ inch* b. *ASTM, 1¼ x 1¼ inch* c. *Watertown, 1 x 4½ inch*

Figure 21– Segregation structure developed by deep acid etch on the different keel casting designs

the high and low values reported by two producers of the steels on similar tests made by them are also included in these figures.

Discussion of Test Results

A variation in Charpy impact values exists between specimens, but there is no fixed pattern for this variation across the keel casting. The resulting variation is summarized in Table 6; however, the average percent variation is 33 percent.

The horizontal positioned specimens in most cases exhibit poorer properties than the vertically positioned specimens even though the horizontal specimens came from the lower part of the keel leg.

TABLE 6
Variations in Impact Values Found in Keel Test Castings

Keel Type inches	Steel	Charpy Impact Variation ft-lbs.	Variation Percent †	Keel Average ft. lbs.	Keel Average R_c
1 x 4	Cr-Mo	58 to 75	23	68	23
	Mn-Cr-Mo #2	24 to 46	48	35	24
	Ni-Cr-Mo	33 to 48	31	40	23
	Mn-Ni-Cr-Mo #1	18 to 29	38	23	23
	Mn-Ni-Cr-Mo #4	29 to 44	34	36	25
1-3/4 x 2-3/4	Mn-Cr-Mo #2	30 to 46	35	40	23
	Ni-Cr-Mo	35 to 52	33	44	22
	Mn-Ni-Cr-Mo #4	35 to 44 ‡	23	39	26
1 x 1-1/4	Mn-Cr-Mo #2	29 to 39	26	33	25

† Ratio: $\frac{\text{Variation}}{\text{Highest impact value}}$
‡ Horizontal position only

However, the vertical specimens alone showed a variation of 27 percent. This is different than was anticipated as it was thought that the lower part of the keel leg would be the most homogenous. Cross sections of the keel casting designs, after deep acid etching, are shown in Figure 21. These castings show no discontinuities in 1 percent sensitive X-ray radiographs and apparently merely indicate a segregation pattern.

The horizontal specimens located in the 1¾ x 2¾ inch keel produce values similar to those positioned vertically.

It appears from the test data that the 1¾ x 2¾ inch keel gives more consistent results and higher values than obtainable from the 1 x 4 inch, or the 1 x 1¼ inch keel. A direct comparison of the three types of keel castings was secured in the Mn-Cr-Mo No. 2 composition:

1 x 1¼ in. keel	33 ft. lbs.	25 R_c
1 x 4 in. keel	35 ft. lbs.	24 R_c
1¾ x 2¾ in. keel	40 ft. lbs.	23 R_c

The only course of action that was justified, in the Research Committee's opinion, was to continue to take test specimens from the center of the keel leg for impact testing and to reject those values that fall considerably out of line and continued with further testing. This is the practice employed in the studies reported in the following sections of the report.

Summary of Specimen Location in Keel Castings

1—A variation of about 33 percent exists between the –40 degree F Charpy V-notch impact values in any of the quenched and tempered keel test castings. However, there is no fixed pattern for this variation within the keel test casting.

2—The horizontally positioned specimens exhibit poorer impact values than the vertical specimens because of their location rather than their direction.

3—The 1¾ x 2¾ inch keel apparently produces the highest impact values.

SECTION V
THE EFFECT OF HOMOGENIZATION TEMPERATURE AND TIME ON TOUGHNESS

The effects of homogenization heat treatment on cast steels have been studied by two groups of investigators. [2, 3] Section thickness of 1 and 2 inches for carbon and low-alloy cast steels have been studied at homogenizing heat treatments of from 2 to 12 hours at temperatures of 1650 to 2250 degrees F. Quench and tempering as well as normalizing heat treatments were employed following homogenization.

These investigations very emphatically point out that no significant effects or trends from the homogenizing treatments were observed on the austenitic grain size, hardenability, notched-bar toughness of V-notch Charpy specimens at room and subatmospheric temperatures, temper-brittleness susceptibility, or tensile properties.

Also, the studies showed that the properties of unhomogenized specimens were generally equivalent to those of homogenized steel. Any deviations that arose could be more closely connected to the variation that existed between Charpy bars because of their position in the test casting, than with any influence associated with the homogenization heat treatment.

It would seem, from these negative results, that there would be little to be gained by further rechecking the original studies. There were three reasons, however, that contributed to including homogenization studies in this research: (1) steel foundrymen continued to use long homogenization times and in some cases high homogenization temperatures (above 1700 degrees F); (2) homogenization studies have not been made on the more highly alloyed of the low-alloy steels, such as the Cr-Mo and the Mn-Ni-Cr-Mo steels of this investigation; and (3) the effect of homogenization on properties of cast steel sections greater than 2 inches have not been reported in the technical literature.

Studies were likewise carried out on the carbon and the lightly alloyed steels in one-inch sections in order to again impress on the steel foundrymen that homogenization treatments are unnecessary.

Homogenizing Procedure

Keel casting legs, 1 x 4-inch cross section, 3- and 6-inch blocks were employed in the homogenization studies. Castings were heated at four temperatures: 1650, 1750, 1850 and 2050 degrees F and were held

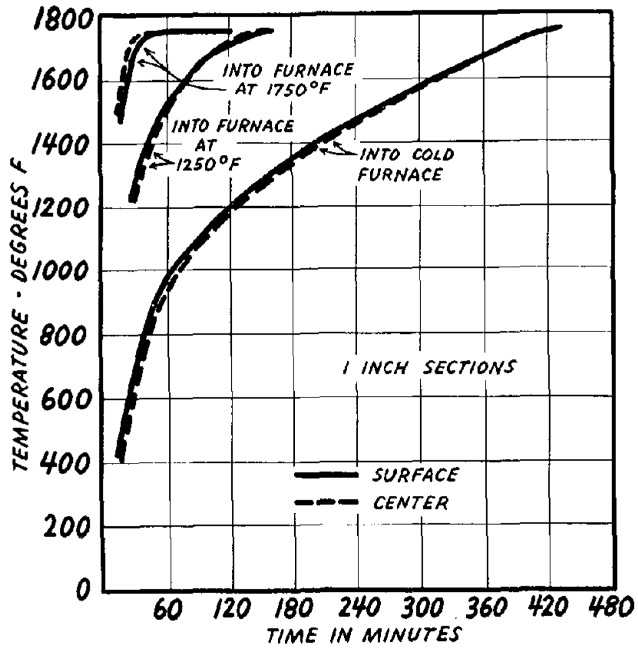


Figure 22—Heating to 1750 degrees F of 1-inch sections of Cr-Mo and Mn-Ni-Cr-Mo cast steels at National Malleable Steel Castings Company (in the production furnace)

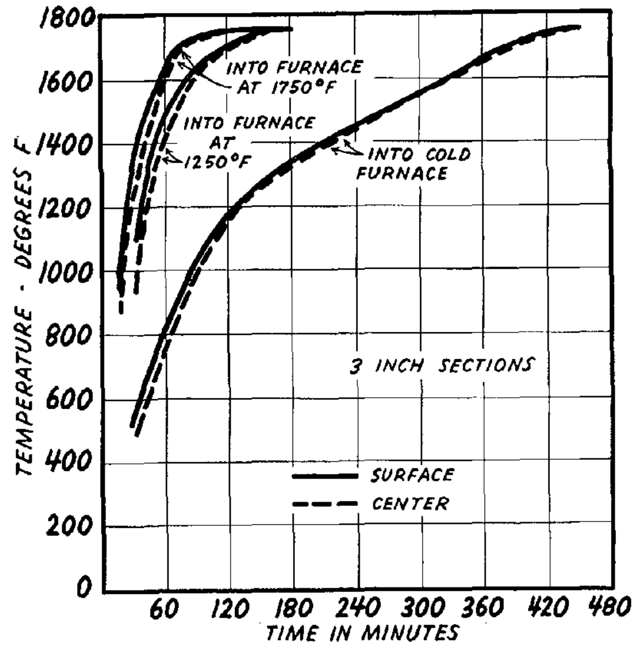


Figure 23—Heating to 1750 degrees F of 3-inch sections of Cr-Mo and Mn-Ni-Cr-Mo cast steels in the production furnace at National Malleable & Steel Castings Company

at each temperature for four times: 15, 30, 90 and 300 minutes and then air cooled. Test specimens without any homogenization treatment were also included in the study.

All castings were then given the quenching heat treatment which consisted of heating to 1650 degrees F for 90 minutes, water quenching and immediately tempering to a prescribed hardness level for a prescribed time followed by water quenching. Details of the procedure are given in Table 7.

Heat Transfer Curves

Heating curves were secured with thermocouples located at the surface and center of each of the three section size test castings for one homogenizing temperature. Curves were prepared for each section size for three conditions of heating: (a) slow heating of the sections by allowing the coupon to be placed in a cold furnace and heated with the furnace to the homogenizing temperature; (b) fast heating of the sections by placing the sections in a furnace at the homogenization temperature; (c) a medium heating rate by placing the sections in a furnace at a temperature just below the critical range and then furnace heating the sections to the homogenization temperature.

The three research laboratories employed different types and sizes of furnaces; therefore, the heating rates were different. Section size and load size also affect the rate of heat transfer. Different composition steels, as employed in this research, do not affect the rate of heat transfer. The heat transfer curves for the 3 research agencies for various section sizes and rates of heating are shown in Figures 22 to 27.

The heat transfer charts bring out certain indisputable facts:

1—Large production furnaces are slow heating and the center of a section reaches the heat treating temperature about the same time as the surface reaches temperature.

TABLE 7

Heat Treating Conditions for Studying the Effect of Homogenization Variables

Homogenization Temperature, °F, None, 1650, 1750, 1850, 2050
Homogenization Time, min. 0, 15, 30, 90, 300
Quenching Conditions: 1650°F for 90 minutes, water quenched, tempered and water quenched. Carbon steel - 1600°F for 60 minutes, water quenched, tempered, air cooled

Steel	Section Thickness in.	Temper to BHN	Tempering Temp. °F	Time, min.
C	1	200	1150	30
Mn-B	1	200	1200	30
Mn-B	3	200	1200	30
Mn-Cr-Mo #1	1	300-320	1125	30
Mn-Cr-Mo #1	3	285	1150	30
Cr-Mo	1	320	1150	30
Cr-Mo	1	250	1250	30
Cr-Mo	3	250	1250	30
Cr-Mo	6	250	1250	30
Mn-Ni-Cr-Mo	3	250	1250	30

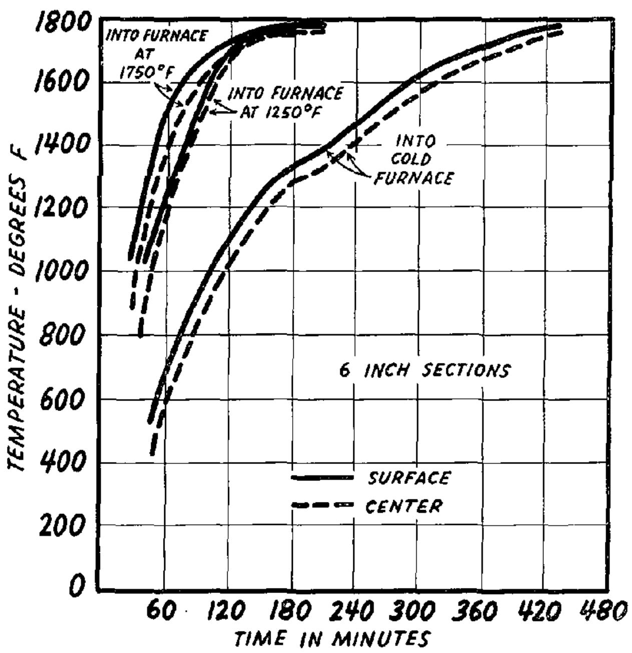


Figure 24—Heating to 1750 degrees F of 6-inch sections of Cr-Mo and Mn-Ni-Cr-Mo cast steels in the production furnace at National Malleable & Steel Castings Company

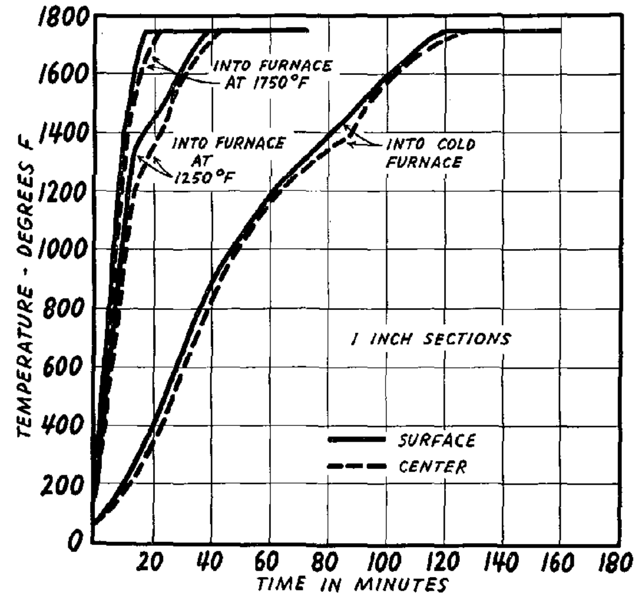


Figure 25—Heating to 1750 degrees F of 1-inch section of Mn-Cr-Mo and Mn-B cast steels in the experimental furnace at Pacific Car & Foundry Company

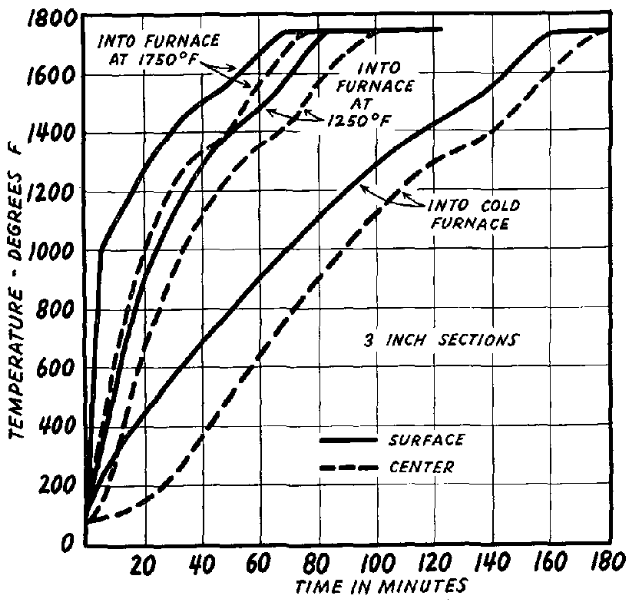


Figure 26—Heating to 1750 degrees F of 3-inch sections of Mn-Cr-Mo and Mn-B cast steels in the experimental furnace at Pacific Car & Foundry Company

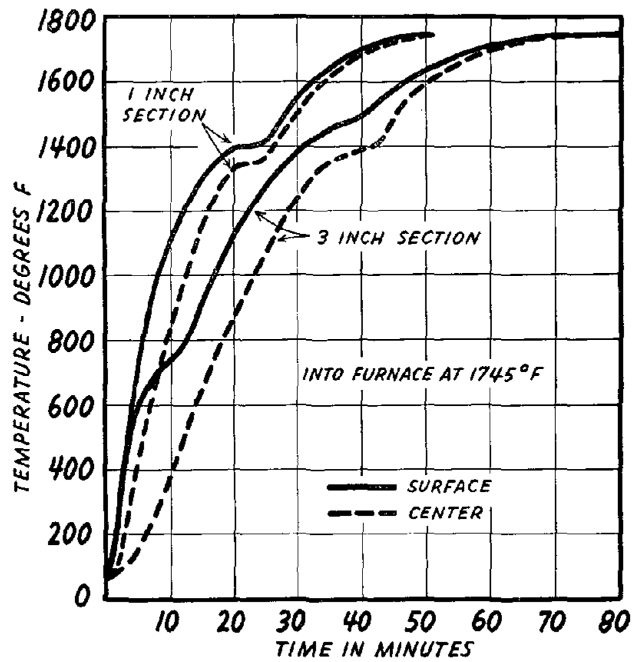


Figure 27—Heating to 1745 degrees F of 1- and 3-inch sections of carbon cast steel in the experimental furnaces of the Steel Castings Institute of Canada

2—The saving in heating time in production furnaces is appreciable if castings are placed into a furnace that is maintained at temperature rather than heating the furnace up with the castings.

3—The temperature gradient in castings heated in small, fast-heating furnaces is also slight. Only in one case was a large temperature gradient of 100 degrees observed in the fast heating of a 1-inch section. The surface reached a temperature of 1750 degrees in 16 minutes but it took 22 minutes for the center of the 1-inch casting to reach the 1750 degree heat treating temperature.

The time for castings of 1-, 3- and 6-inch sections to reach a uniform temperature when placed in a production-type furnace at temperature is not related on a direct ratio basis to the section thickness. For example, the time required for the various sections to reach temperature were 1 inch – 75 minutes, 3 inch – 120 minutes, and 6 inch – 150 minutes.

Castings that are freely accessible to the heat of the furnace do not have drastic temperature gradients within the casting when these castings are near the heat treating temperature even though they receive very fast heating such as that resulting from placing cold castings in hot furnaces.

Toughness Values After Homogenizing

Carbon Cast Steel . . . A study of Table 8 will reveal that neither the homogenization temperature nor the time has any significant influence on the quenched and tempered properties of carbon cast steel. Toughness and strength values for carbon cast steel without homogenization treatment are equal to those having any specified homogenization treatment. The values are so nearly alike that there

TABLE 8

Carbon Cast Steel; 1-inch Section
Effect of Homogenization Temperature and Time on the Mechanical Properties

HEAT TREATMENT: Homogenize—none, 1650, 1750, 1850 and 2050°F for 0, 15, 30, 90 and 300 minutes, air cooled.
Harden—1600°F, 1 hour, water quenched
Temper—1150°F, 30 minutes, air cooled

Mechanical Property	Homogenization Temp. °F	Homogenization Time (minutes) 0	15	30	90	300
Charpy V-Notch Impact at +70°F (ft-lbs)	none†	50	—	—	—	—
	1650	—	52	54	56	60
	1750	—	54	55	53	56
	1850	—	58	62	56	53
	2050	—	59	54	57	63
Charpy V-Notch Impact at −40°F (ft-lbs)	none†	27	—	—	—	—
	1650	—	27	25	26	22
	1750	—	25	26	27	28
	1850	—	25	26	27	28
	2050	—	27	27	29	29
BHN	none†	212	—	—	—	—
	1650	—	205	200	195	195
	1750	—	195	200	195	205
	1850	—	200	195	195	210
	2050	—	200	200	205	200
Tensile Strength (1000 psi)	none†	93.5	—	—	—	—
	1650	—	93.2	93.1	93.8	92.6
	1750	—	93.2	93.1	92.3	94.7
	1850	—	91.8	91.9	93.2	94.5
	2050	—	95.3	95.3	95.0	96.4
Yield Strength (1000 psi)	none†	66.7	—	—	—	—
	1650	—	69.4	64.8	65.8	64.4
	1750	—	65.6	64.9	65.8	66.2
	1850	—	63.3	63.1	66.5	66.1
	2050	—	65.4	66.6	65.8	68.5
Elongation %	none†	25.3	—	—	—	—
	1650	—	25.0	27.0	27.2	28.7
	1750	—	26.0	26.5	23.0	24.0
	1850	—	25.2	25.2	26.5	25.0
	2050	—	26.0	24.7	26.2	24.7
Reduction of Area (%)	none†	52.7	—	—	—	—
	1650	—	50.1	53.5	53.0	52.2
	1750	—	51.1	51.7	48.9	49.8
	1850	—	51.3	51.1	49.7	47.5
	2050	—	56.5	53.7	54.5	54.2

† No homogenization treatment given; only quench and temper treatment employed.

is no advantage to the reader in attempting to chart these values.

The microstructures resulting from selected homogenization treatments are illustrated in Figure 28. A slight coarsening of the grain size is noted for the high-temperature long-time homogenization treatment.

Mn-B Cast Steel . . . The manganese-boron cast steel was investigated in the 1- and 3-inch sections; however, only the 1850 degree F homogenization temperature was employed with the 3-inch sections. The test results are tabulated in Tables 9 and 10.

There is very little variation in impact properties regardless of the temperature or time of homogenization and therefore, the short-time low-temperature homogenization values are as good as any for either the 1- or 3-inch sections.

The +70 degree F impact properties were very similar in both the 1- and 3-inch sections; however, at −40 degrees F the 3-inch impact values fell off sharply. The reason for this is noticeable by referring to a comparison of the 1- and 3-inch section microstructures as illustrated in Figure 29. The tensile properties and +70 degree impact results were good for 3-inch sections but the steel is not acceptable for low-temperature use at sections much above 1-inch thickness.

The variation in impact properties is generally a function of hardness as can be seen in Figure 30a wherein the +70 degrees F Charpy values are plotted as a function of hardness. This again indicates that neither time nor temperature of homogenization is important in itself but merely as it affects the hardness and microstructure.

Mn-Cr-Mo Cast Steel . . . Homogenization studies on the Mn-Cr-Mo steel relating to the 1- and 3-inch sections, with only one homogenization temperature being employed for the 3-inch section, were conducted. The test results are given in Tables 11 and 12.

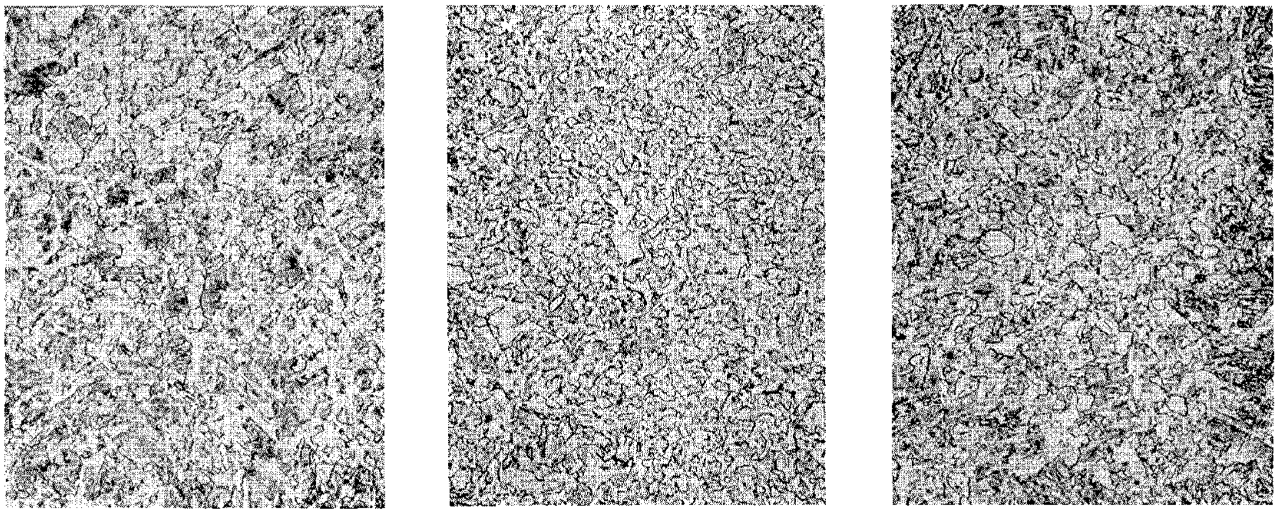
TABLE 9

Mn-B Cast Steel - 1-inch Section
Effect of Homogenization Temperature and Time on Toughness and Strength

HEAT TREATMENT: Homogenize—none, 1650, 1750, 1850 and 2050°F for 0, 15, 30, 90 and 300 minutes, air cooled.
Harden—1650°F, 90 minutes, water quenched
Temper—1200°F, 30 minutes, water quenched

Mechanical Property	Homogenization Temp. °F	Homogenization Time (minutes) 0	15	30	90	300
Charpy V-Notch	none	38	—	—	—	—
Impact at	1650	—	43	43	41	38
+70°F (ft-lbs)	1750	—	41	38	38	43
	1850	—	39	38	42	39
	2050	—	39	38	—	—
Charpy V-Notch	none	29	—	—	—	—
Impact at	1650	—	29	28	31	30
−40°F (ft-lbs)	1750	—	30	32	28	38
	1850	—	35	35	37	34
	2050	—	35	32	—	—
BHN	none	229	—	—	—	—
	1650	—	209	205	214	217
	1750	—	218	217	233	221
	1850	—	231	227	221	229
	2050	—	229	233	—	—

Homogenization Temp. °F	Homogenization Time min.	Tensile Strength 1000 psi	Yield Strength 1000 psi	Elon. in 2" %	Red. of Area %	Brinell
none	0	112.2	96.2	16.5	34.3	229
1650	90	108.2	93.4	22.0	42.8	214
1750	15	107.2	94.5	19.5	39.8	221
1850	15	112.2	102.5	18.0	40.2	231
2050	30	109.2	97.8	18.0	31.2	229



a. No homogenization

b. Homogenization at a low temperature for short time (1650°F - 15 min.)

c. Homogenization at a high temperature for a long time (2050°F - 300 min.)

Figure 28—Carbon cast steel microstructures showing the effect of homogenization on the microstructure at the center of a one-inch section followed by water quenching from 1650 degrees F and tempering at 1150 degrees. 200X Nital etch

The hardness values vary from 290 to 337 in Table 11 and for this reason the impact values may be of greater variation than should be expected. However, if the impact properties of the steel, as listed in Table 11, are plotted it will be observed that, in general, impact strength is a function of hardness rather than one of prior heat treatment. This can be seen by referring to the Mn-Cr-Mo –40 degree F im-

TABLE 10

Mn-B Cast Steel - 3-inch Section
Effect of Homogenization Temperature and Time on the Mechanical Properties

HEAT TREATMENT: Homogenize—1850°F for 15, 30 and 90 minutes, air cool
Harden—1650°F, 90 minutes, water quench
Temper—1200°F, 30 minutes, water quench

Mechanical Properties	Homogenization Temp. °F	Time, minutes 15	30	90
V-Charpy +70°F ft-lbs	1850	42	44	46
V-Charpy –40°F ft-lbs	1850	11	15	11
BHN		198	197	205

		Tensile 1000 psi	Yield 1000 psi	Elon. %	R.A. %
Tensile Properties	1850 at 90 min.	105.0	85.5	23	50.8

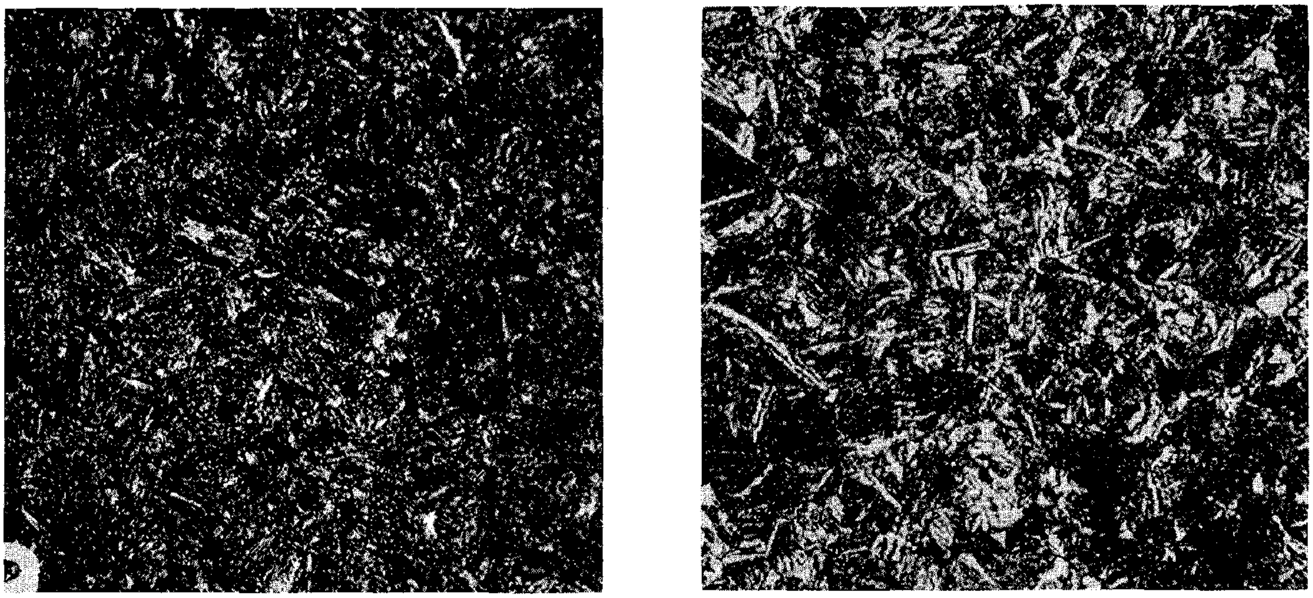
TABLE 11

Mn-Cr-Mo, 1-inch Section
Effect of Homogenization Temperature and Time on Mechanical Properties

HEAT TREATMENT: Following Homogenization: Heated to 1650°F for 90 minutes; water quench. Tempered to 300-320 Brinell Hardness (1125°F for 30 minutes)

Homogenization Temp. °F	Time min.	BHN	Charpy V-Notch Impact ft-lbs. +70°F	–40°F	–80°F
none	0	337	33	19	13
1650	15	323	34	25	17
	30	321	31	31	16
	90	302	37	35	38
	300	321	37	27	22
1750	15	307	38	36	33
	30	307	38	35	33
	90	297	42	44	37
	300	298	43	38	40
1850	15	311	45	40	41
	30	306	39	39	35
	90	321	34	25	26
	300	290	44	39	41
2050	15	302	40	34	28
	30	307	41	38	35

		Tensile 1000 psi	Yield 1000 psi	Elon. %	R.A. %	BHN
none	0	150.7	141.2	10.0	19.0	337
1650	90	141.2	130.0	13.8	31.0	302
1750	30	164.2	155.2	10.5	19.6	337
1850	15	149.2	139.5	12.5	30.0	317
2050	30	144.2	132.5	13.3	32.9	302



a. 1-inch section. Homogenize 1850°F, 15 minutes *b. Center of 3-inch section. Homogenize 1850°F, 90 min.*

Figure 29—Mn-B microstructures showing the effect of section size and homogenization. Subsequent heat treatment was water quenching (1550°F) and tempering (1200°F) 500X Nital etch

pact strength curve for the 1-inch section as illustrated in Figure 30a. Figure 30b illustrates the character of the variations obtained. All that can be said on the basis of trends is that: (1) there is a slight fall off in impact values as the testing temperature drops from +70 to –80 degrees F; (2) homogenization temperature and time is not too significant in the development of pronounced trends in toughness properties.

The toughness values for the 3-inch section are not much below those of the 1-inch section in view of the difference in hardness levels of the test results and it is indicated that the steel is acceptable for

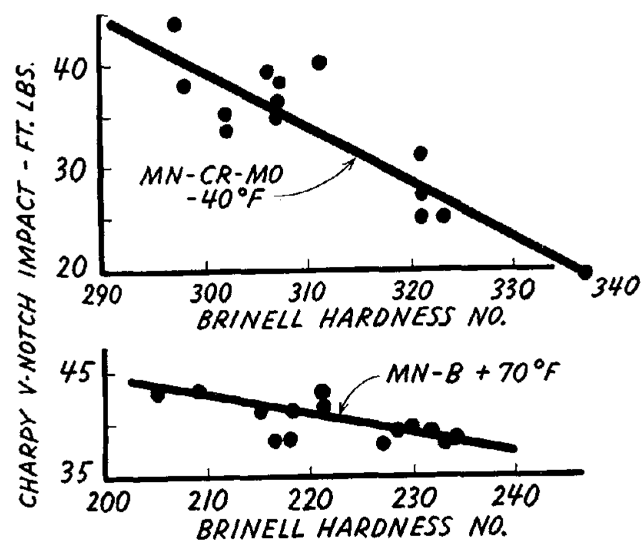


Figure 30a—Relation of hardness and impact properties for two low alloy cast steels.

TABLE 12
Mn-Cr-Mo, 3-inch Section Effect of Homogenization Temperature and Time on Mechanical Properties

HEAT TREATMENT: Following homogenization: Heated to 1650 degrees F 90 minutes, water quenched. Tempered to 250 BHN (1150°F 30 min.)

Homogenization Temp. °F	Time min.	BHN	Charpy V-Notch Impact ft-lbs. +70°F	–40°F	–80°F
1750	15	283	50	35	30
1750	30	289	48	33	23
1750	90	283	53	32	20
1750	300	272	51	26	26
		Tensile 1000 psi	Yield 1000 psi	Elon. %	R.A. %
1750	15	134.0	120.0	11.3	18.3

quench and tempering thicknesses up to about 3 inches. Increasing the homogenization time at any one homogenizing temperature did not improve the toughness values.

The effect of homogenization on the Cr-Mo cast steel was ascertained by toughness studies on 1-, 3- and 6-inch sections at a hardness level of 250 Brinell and also the 1-inch section at 300 Brinell. The Brinell hardness value was converted from the average of 8 Rockwell C readings taken on the impact bars. The values obtained are reported in Tables 13, 14, 15 and 16.

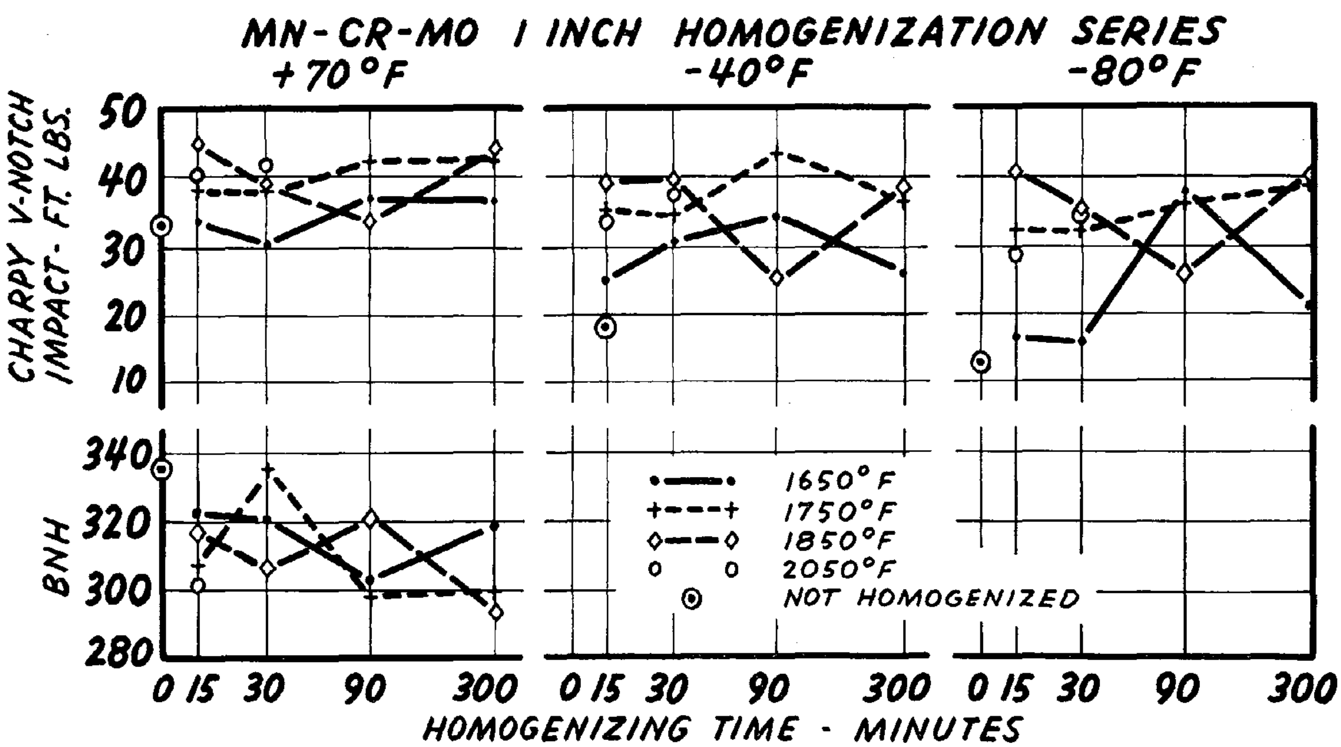


Figure 30b—Mn-Cr-Mo 1-inch section. The effect of homogenization time and temperature on the Charpy V-notch impact properties.

There is no advantage in charting the values because they are a series of horizontal lines with not too much difference in values between the +70 and −80 degree F impact results. The tensile values are constant regardless of the time or temperature of homogenization.

The effect of homogenization temperature on the section thickness is shown in Figure 31. In this case all the impact values at the various times for one homogenization temperature were averaged together to establish a point on the chart. It will be observed that the 3-inch section produced the lowest values. A similar condition was repeated in other studies of this research. Apparently the solidification pattern of the 3-inch section is such that the location of the impact specimen in this section is in a critical segregation zone. The location of the specimens in the 6-inch section is outside the segregation zone and, hence, the impact values are somewhat higher. Also, the 3-inch section was tempered to a slightly higher hardness which may affect the impact slightly. All lines are horizontal indicating that neither temperature nor time of homogenization improves the values. In fact, no homogenization at all prior to the quench and temper heat treatment produces the same values.

The important effect that different hardness levels have on the impact properties for varying time and

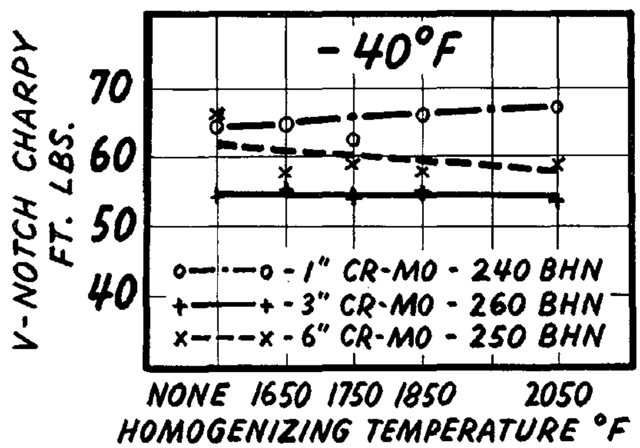


Figure 31—The effect of homogenization temperature and section thickness on the Charpy V-notch impact properties of Cr-Mo steel at −40 degrees F. All values at the various homogenization times were averaged to plot a point for each homogenization temperature. Quenched at 1650 degrees F and tempered to hardnesses shown on chart.

temperature of homogenization is shown in Figure 32. This study, though confined to 1-inch sections, shows that the same flat lines are obtained, and indicates that the homogenization temperature or time has no effect on the character of the quenched and tempered impact property values.

Representative microstructures of the Cr-Mo steel following quench and tempering, but having different homogenization temperature and times, are shown for 1-, 3- and 6-inch sections in Figure 33. The zephiran chloride etch was used to bring out possible grain boundary conditions.

There is very little difference between the microstructures developed when a low or high homogenizing temperature is employed. In fact, the section size shows greater changes in microstructure than does the effect of homogenization.

Mn-Ni-Cr-Mo Cast Steel . . . Homogenization studies on the Mn-Ni-Cr-Mo steel form a pattern similar to the results of the other alloy cast steels previously given. Only the 3-inch section was studied as to the effect of homogenization time and temperature. The tabulated results are given in Table 17. Neither homogenization temperature nor time at temperature has any influence on the quenched and tempered properties of this steel. The impact values for each testing temperature all fall within a very narrow band indeed, considering the present variation that is normal for impact testing. One thing that definitely can be said about the data of Table 17 is that the homogenized impact values are definitely below those secured without homogenization. The microstructure of the Mn-Ni-Cr-Mo steel under one condition of homogenization is shown in Figure 34. Homogenization at various temperatures had very little effect on the microstructure of this steel.

Summary of Homogenization

The effect of homogenization temperature and time on the toughness properties of quenched and

TABLE 13

Cr-Mo, 1-inch Section—250 Brinell Range
The Effect of Homogenization Temperature and Time on the Toughness and Tensile Properties

HEAT TREATMENT: Homogenize—none, 1650, 1750, 1850 and 2050°F for 15, 60 and 320 minutes
Harden—1650°F, 90 minutes, water quench
Temper—1250°F, 2 hours, water quench

Homogenization Temp. °F	Time min.	BHN	Charpy V-Notch Impact ft-lbs. +70°F	−40°F	−80°F
none	none	246	68	62	49
1650	15	244	69	66	65
	60	246	70	64	63
	320	246	70	67	62
1750	15	245	67	65	56
	60	248	71	63	66
	320	244	63	61	45 †
1850	15	234	70	63	61
	60	234	77	72	70
	320	237	76	66	68
2050	15	231	70	67	68
	60	231	73	68	50 †
	320	233	71	68	63

°F	min.	BHN	Tensile 1000 psi	Yield 1000 psi	Elon. %	R.A. %
1650	15	241	117.1	97.1	18.0	49.9
		241	118.5	92.8	17.5	47.5
1750	60	255	117.6	99.6	20.0	54.8
		248	118.5	99.6	18.5	52.2
1850	15	241	117.0	96.4	18.5	51.7
		241	118.3	93.7	17.0	47.3
2050	60	255	119.2	99.4	14.0	34.7
		262	119.7	97.4	15.0	34.9

† Values unrealistic and out of line. Additional rechecking undoubtedly needed.

TABLE 14

Cr-Mo, 1-inch Section—300 Brinell Range
The Effect of Homogenization Temperature and Time on the Toughness and Tensile Properties

HEAT TREATMENT: Homogenize—none, 1650, 1750, 1850, 2050°F for 15, 60, 320 minutes
Harden—1650°F, 90 minutes, water quench
Temper—1150°F, 30 minutes, water quench

Homogenization Temp. °F	Time min.	BHN	Charpy V-Notch Impact ft-lbs. +70°F	−40°F	−80°F
none	none	300	48	47	46
1650	15	303	50	49	46
	60	296	49	50	44
	320	300	51	49	50
1750	15	296	48	48	42
	60	295	53	52	47
	320	300	55	51	46
1850	15	303	50	50	49
	60	290	48	44	46
	320	295	48	49	45
2050	15	296	48	46	42
	60	300	50	42	32
	320	290	48	44	32

°F	min.	BHN	Tensile 1000 psi	Yield 1000 psi	Elon. %	R.A. %
none	none	311	150.0	124.8	13.0	46.0
1650	15	302	149.8	123.8	13.0	44.1
		302	147.9	122.8	13.5	42.3
1750	60	311	147.2	123.8	13.0	41.0
		311	148.0	124.3	12.0	38.8
1850	15	311	147.9	117.3	12.0	33.5
		302	147.0	122.3	12.5	38.0
2050	60	311	147.2	125.3	12.0	33.6
		302	146.3	124.8	12.0	33.3

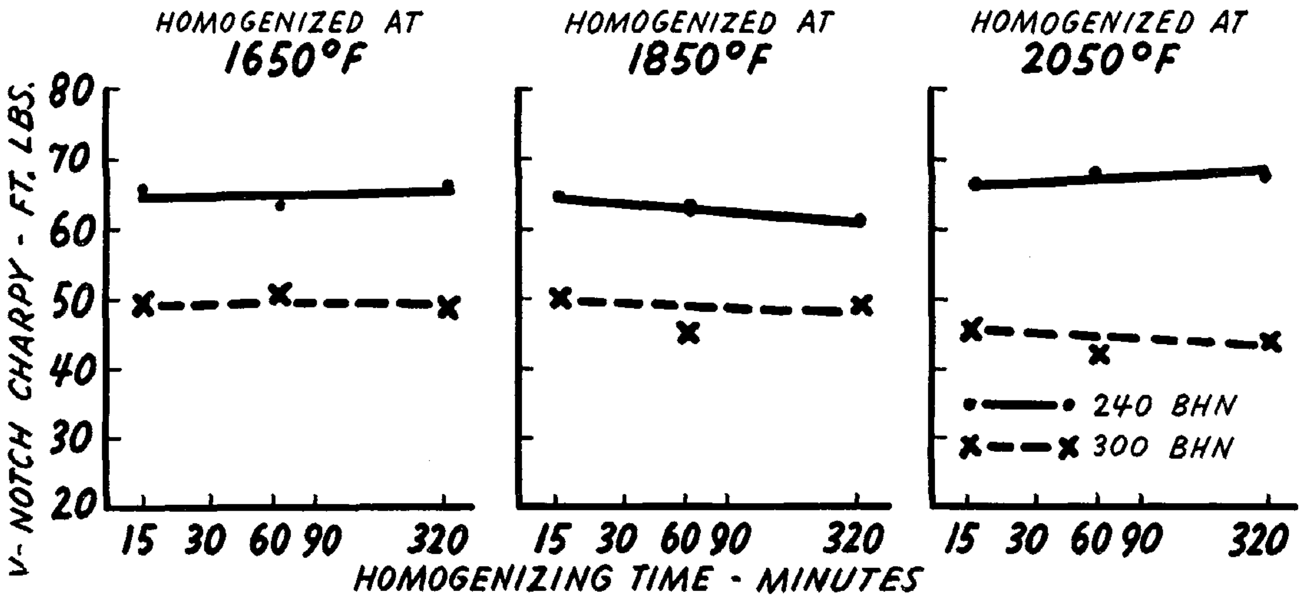


Figure 32—Cr-Mo 1-inch thick section, –40 degrees F. The effect of homogenization on the Charpy V-notch impact properties of Cr-Mo cast steel quenched 1650 degrees F and tempered to the hardnesses shown on the chart.

TABLE 15

Cr-Mo, 3-inch Section—250 Brinell Range
The Effect of Homogenization Temperature and Time on the Toughness and Tensile Properties

HEAT TREATMENT: Homogenize—none, 1650, 1750, 1850, 2050°F for 15, 60 and 320 minutes

Harden—1650°F, 90 minutes, water quench

Temper—1250°F, 30 minutes, water quench

Homogenization Temp. °F	Time min.	BHN	Charpy V-Notch Impact ft-lbs. +70°F	-40°F	-80°F
none	none	260	61	55	39
1650	15	265	65	55	44
	60	261	57	52	53
	320	255	61	58	46
1750	15	265	53	52	49
	60	267	58	55	44
	320	261	55	52	42
1850	15	270	59	58	48
	60	273	52	50	39
	320	263	62	56	52
2050	15	260	61	53	47
	60	261	61	59	50
	320	258	57	48	43

°F	min.	BHN	Tensile 1000 psi	Yield 1000 psi	Elon. %	R.A. %
none	none	269	125.7	102.7	11.0	31.9
1650	15	255	119.2	88.6	12.0	25.7
1750	60	269	119.3	92.2	10.0	20.6
1850	15	255	113.3	88.7	7.5	35.4
2050	15	255	119.7	89.8	13.0	35.3

TABLE 16

Cr-Mo, 6-inch Section—250 Brinell Range
The Effect of Homogenization Temperature and Time on the Toughness and Tensile Properties

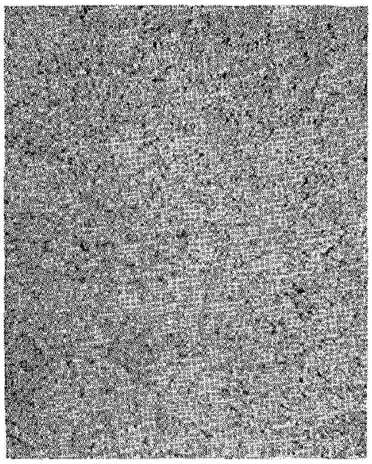
HEAT TREATMENT: Homogenize—none, 1650, 1750, 1850, 2050°F for 15, 60, 320 minutes

Harden—1650°F, 90 minutes, water quench

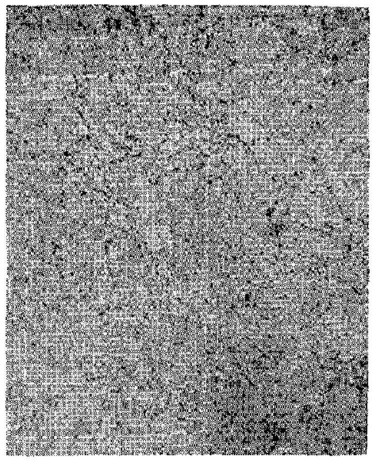
Temper—1250°F, 30 minutes, water quench

Homogenization Temp. °F	Time min.	BHN	Charpy V-Notch Impact ft-lbs. +70°F	-40°F	-80°F
none	none	264	70	64	33
1650	15	254	59	56	47
	60	255	61	58	55
	320	255	58	59	49
1750	15	247	61	55	54
	60	247	66	57	51
	320	245	71	64	62
1850	15	255	64	58	44
	60	254	59	57	44
	320	253	64	58	39
2050	15	247	58	55	46
	60	256	61	59	48
	320	253	61	59	41

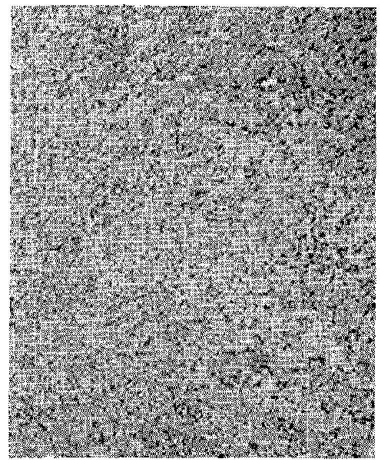
°F	min.	BHN	Tensile 1000 psi	Yield 1000 psi	Elon. %	R.A. %
none	none	241	116.3	86.9	15.0	36.3
1650	60	277	127.3	93.8	12.5	38.8
1750	320	277	129.6	103.3	15.0	48.1
1850	60	269	128.1	100.8	14.0	43.5
2050	60	269	129.1	98.0	10.5	28.0



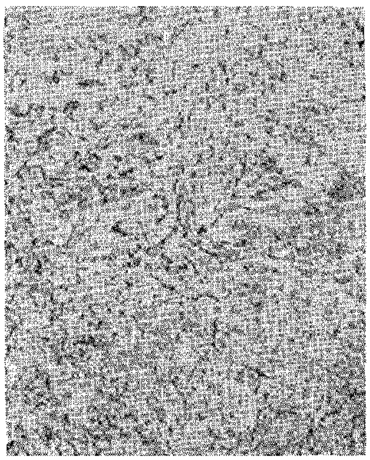
a. 1-inch section.
Homogenized 1650°F, 15 min.



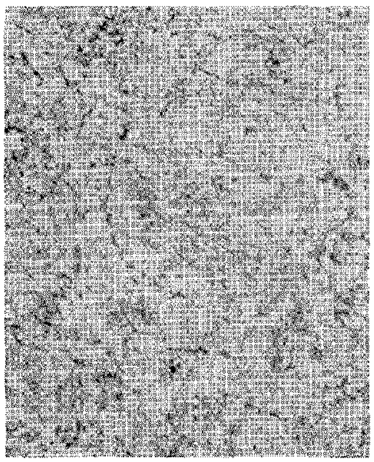
b. 3-inch section.
Homogenized 1650°F, 15 min.



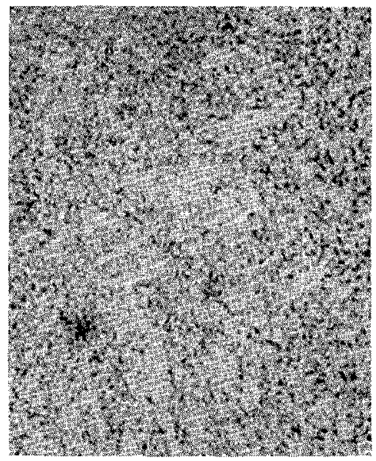
c. 6-inch section.
Homogenized 1650°F, 15 min.



d. 1-inch section.
Homogenized 2050°F, 60 min.



e. 3-inch section.
Homogenized 2050°F, 60 min.



f. 6-inch section.
Homogenized 2050°F, 60 min.

Figure 33—Microstructure of Cr-Mo cast steel homogenized at 1650 and 2050 degrees F for 90 minutes, water quenched and tempered to 250 Brinell.

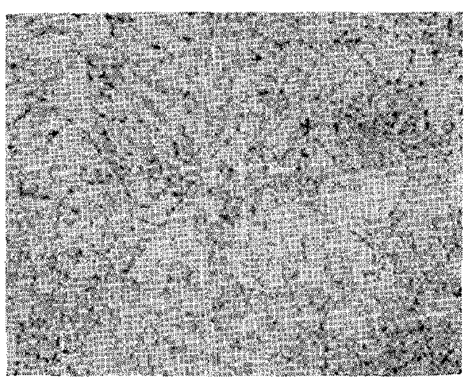


Figure 34—Microstructure of 3-inch section of Mn-Ni-Cr-Mo cast steel homogenized at 1750 degrees F for 60 minutes followed by heating to 1650 degrees F for 90 minutes, water quenched and tempered to 255 Brinell.

TABLE 17

Mn-Ni-Cr-Mo, 3-inch Section—250 Brinell Range The Effect of Homogenization Temperature and Time on the Toughness and Tensile Properties

HEAT TREATMENT: Homogenize—none, 1650, 1750, 1850, 2050°F for 15, 60, 320 minutes
Harden—1650°F, 90 minutes, water quench
Temper—1250°F, 30 minutes, water quench

Homogenization Temp. °F	Time min.	BHN	Charpy V-Notch Impact ft-lbs. +70°F	−40°F	−80°F
none	none	245	40	35	30
1650	15	256	28	21	24
	60	247	34	23	16
	320	247	30	23	11
1750	15	254	32	21	18
	60	254	34	21	19
	320	254	35	25	18
1850	15	247	28	19	17
	60	245	32	20	17
	320	242	30	18	12
2050	15	252	30	25	19
	60	252	31	22	22
	320	252	39	28	20

°F	min.	BHN	Tensile 1000 psi	Yield 1000 psi	Elon. %	R.A. %
none	none	269	122.0	100.3	12.2	24.4
1650	60	262	117.9	99.9	7.5	12.0
		248	122.0	102.1	11.0	23.9
1750	320	255	119.1	100.8	8.5	14.1
		262	115.5	100.3	8.0	13.0
1850	60	255	118.7	97.5	14.5	34.7
		241	117.2	98.0	11.0	21.4
2050	320	255	118.9	94.2	13.5	33.2

tempered cast steels can be summarized from the test studies as follows:

1—Increasing the temperature of homogenization above 1650 to 2050 degrees F does not improve the impact or tensile properties of carbon and low-alloy cast steels.

2—Increasing the time of homogenization at any homogenization temperature does not improve the impact or tensile properties of carbon and low-alloy cast steels at any constant hardness level.

3—Section size variations have a slight effect on the impact properties of cast steels; however, they do not influence toughness properties resulting from changing homogenization temperatures or times.

4—The toughness of C, Cr-Mo and Mn-Ni-Cr-Mo steels was not improved by employing a homogenization treatment. Therefore, the extra step of homogenization can be eliminated because the cost and processing time are both reduced without lowering casting quality.

5—The Mn-B steel shows similar toughness and tensile values whether or not a homogenization treatment is used. However, the hardenability of this steel is low, the microstructure is inferior, and impact values are low in 3-inch sections. This steel is not acceptable for low temperature use at sections much above 1-inch thickness.

6—The Mn-Cr-Mo steel toughness values indicate no particular advantage of a homogenization heat treatment. The results suggest that a slight improvement may be obtained by occasional heat treatments; however, the hardness variations are wide and the test data in general indicate that impact strength is more of a function of hardness than of prior heat treatment.

SECTION VI
THE EFFECT OF AUSTENITIZING (QUENCHING) TEMPERATURE AND TIME ON TOUGHNESS

Many foundrymen are of the opinion that the heating temperature employed prior to the quenching operation is significant in determining the character of the mechanical properties obtained. Also, high temperatures are often desired because transferring of castings from the furnace to the quench tanks takes time and it is feared that considerable temperature will be lost.

The studies carried out in this section of the research were planned to show the effect of varying the temperature from which the castings were quenched on the toughness values. Likewise, it was desirable to ascertain whether the time of heating prior to quenching would in any way affect or alter the toughness values.

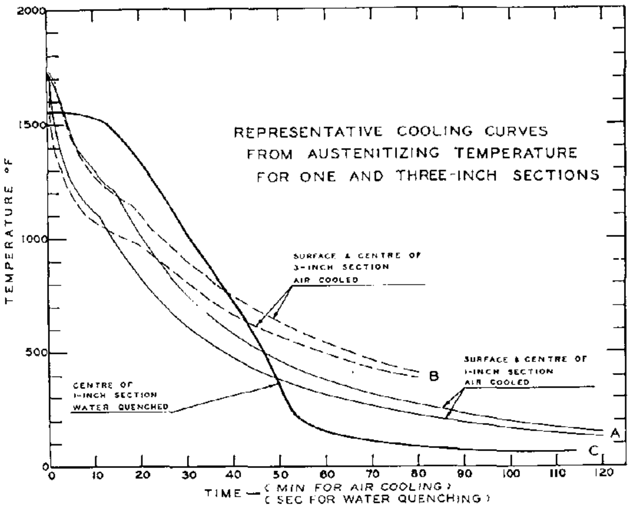


Figure 35—Cooling curves for the carbon cast steel

Steel castings must be well spaced on trays or racks so that they may be uniformly heated to the selected temperature and effectively quenched in liquid. The liquid primarily used in the steel casting industry, for quenching carbon and low-alloy cast steels in water. Water is an excellent quench liquid because it provides a high quenching efficiency. Also, most cast steels fall in the carbon range of 0.20 to 0.40 percent and water quenching of such steels seldom promotes quench cracking unless the steels are rather highly alloyed. In fact, cast steels are noted for their excellent toughness values and adaptability in service which requires a combination of wear and impact resistance properties.

Wrought steel users normally select alloy steels of 0.40 percent carbon content and then quench them in oil whereas steel casting producers select the same alloy but often employ a carbon content of 0.25 to 0.30 percent and water quench the castings. Naturally, the lower carbon content will result in a steel with greater toughness while at the same time securing the tensile strength properties desired.

Quenching Procedure

It was decided to employ homogenization heat treatment in this study since the present normal procedure of steel foundries is to employ a homogenization treatment prior to quenching. The research agencies were permitted to select the homogenization treatment that gave the best results as tabulated in Section V.

Test castings were heated to three different temperatures above the critical range and held at these temperatures for various times followed by water quenching. The test castings were then tempered to a hardness level for a definite period of time, and water quenched.

A series of quenching tests employing interrupted quenching was also made. The test castings were quenched in water until the surface temperature of the bars was 500 degrees F. The castings were then withdrawn from the water and the temperature of the bar allowed to level out some, prior to again quenching in water to bring the castings to 300 degrees F or under.

An example of the interrupted quenching procedure developed is as follows:

1-inch section thickness

1550°F quench - 27 sec., hold in air 60 sec., water quench to 300°F

1650°F quench - 30 sec., hold in air 60 sec., water quench to 300°F

1750°F quench - 33 sec., hold in air 60 sec., water quench to 300°F

Heat Transfer During Quenching

Temperature studies were made during the water quenching operation for the various section thicknesses at each research agency to show the temperature gradients that existed in the section.

The cooling curves for the carbon steel are presented in Figure 35. The graph also includes curves for air cooling as well as water quenching.

Cooling curves for the 1- and 3-inch sections of Mn-B and Mn-Cr-Mo steel are illustrated in Figures 36 and 37. The effect of interrupted quenching is also shown. The castings were removed from the quench when the surface reached 500 degrees F. The center of the section cooled slowly when the interrupted quench was used.

Carbon Steel Quenching Temperatures

The 0.30 percent carbon steel castings were quenched in water and oil from various temperatures after heating for periods of from 15 to 90 minutes. A prior normalizing treatment of 1650 degrees for 30 minutes was given the test castings prior to the hardening treatment. All test bars were tempered to the same conditions of 1150 degrees F for 30 minutes or 200 BHN. The results are given in Table 18.

Both toughness and tensile values indicate that there is no improvement in these properties by employing high quenching temperatures or long heating times prior to quenching. Both the water quenched and oil quenched test values are similar in indicating that no trends can be drawn.

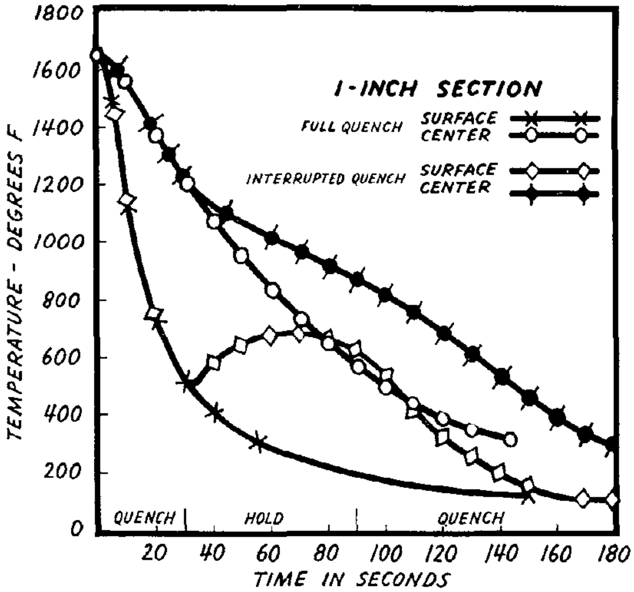


Figure 36—Full quench and interrupted quench curves for 1-inch sections. Mn-B and Mn-Cr-Mo steels. Quenched in water from 1650°F. Interrupted quench; casting withdrawn when surface reached 500°F, held for 60 seconds in air and returned to the quench

Any convenient temperatures would be acceptable for heating prior to the quench. However, this steel showed an Ac_3 temperature of 1540 degrees F and since the austenitizing temperature is usually selected at about 100 degrees F above the Ac_3 temperature it would seem advisable that the 1550 degree heating temperature may not be the proper one to select. Temperatures of 1600 or 1650 degrees F would constitute the proper ones.

There is no advantage in heating carbon cast steels for long times at the quenching temperature; 15 minutes is certainly adequate and 30 minutes is more than ample after the steel comes to temperature.

These results also show that the rate of quenching rather than the temperature and time of austenitizing prior to quenching govern the resultant mechanical properties. The water quench with a cooling rate of about 50 degrees F per second at 1300 degrees F produces better tensile strength and impact strength at –40 degrees F than the oil quench with a slower

TABLE 18

Carbon Steel: 1-inch Section
Effect of Quenching Temperature, Time and Liquid Medium on the Mechanical Properties

HEAT TREATMENT: Normalize—1650°F, 30 minutes, air
Harden—1550, 1650 and 1750°F for 15, 30 and 90 minutes, water and oil
Temper—1150°F, 30 minutes

Mechanical Property	Quenching Temp. °F	Time at Temperature (minutes)					
		Water			Oil		
		15	30	90	15	30	90
Tensile Strength (1000 psi)	1550	95.1	96.0	94.5	90.7	90.6	89.5
	1650	95.3	94.9	94.1	91.3	91.6	90.6
	1750	95.1	93.7	—	91.1	90.7	—
Yield Strength (1000 psi)	1550	67.3	68.0	66.0	59.8	60.4	60.6
	1650	67.3	67.5	67.4	63.7	60.6	60.8
	1750	67.0	66.6	—	61.6	60.7	—
Elongation (%)	1550	26.0	25.5	26.0	27.0	28.2	28.0
	1650	24.8	25.5	24.5	28.7	27.7	27.2
	1750	25.0	24.3	—	28.2	28.2	—
Reduction of Area (%)	1550	57.2	56.9	54.3	52.1	55.9	54.7
	1650	55.0	52.8	51.8	57.6	55.1	52.4
	1750	50.0	50.5	—	55.2	54.1	—
Charpy V-Notch Impact at 70°F (ft-lbs)	1550	49	53	55	56	56	58
	1650	58	53	59	57	57	60
	1750	55	57	—	61	56	—
Charpy V-Notch Impact at –40°F (ft-lbs)	1550	26	33	29	23	21	23
	1650	28	25	25	22	23	24
	1750	26	31	—	25	24	—
Brinell Hardness No.	1550	195	205	195	180	185	180
	1650	200	195	205	185	185	180
	1750	195	200	—	185	180	—

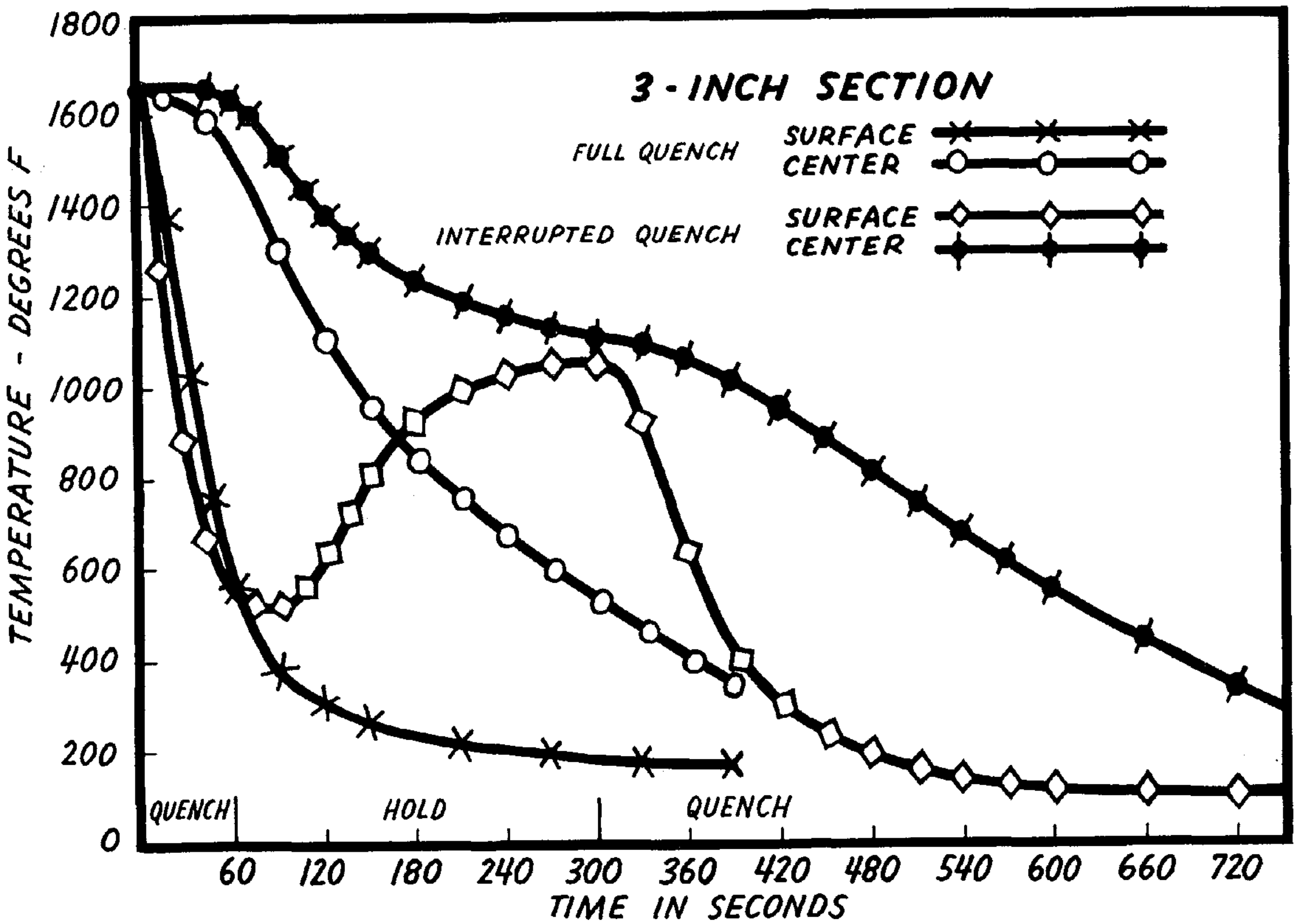


Figure 37—Full quench and interrupted quench curves for 3-inch sections. Mn-B and Mn-Cr-Mo steels. Quenched in water from 1650°F. Interrupted quench: casting withdrawn when surface reached 500°F, held for 240 seconds in air and returned to the quench

cooling rate of about 35 degrees F per second at 1300 degrees F. These impact values would have shown a wide range had the Brinell hardness of both water- and oil-quenched test bars been the same.

Mn-B Quench-Temperature Studies

In the previous carbon steel series a low homogenization temperature was employed whereas, in the Mn-B series, use was made of high-temperature heating for a short time (1850 degrees F for 15 minutes). However, these variations mean little since homogenization temperature and time do not influence the quenched and temper properties.

Studies were made of the effect of a full quench and an interrupted quench. In the latter case the test castings were removed from the quench and held in air for a time interval before again quenching them in water. Interrupted quenching was not studied for the 3-inch section because the steel does not have sufficient depth of hardening to make this practice feasible.

The results of the mechanical property tests are given in Table 19. These values point to the following comments based on the range of times and temperatures employed:

1—Tensile properties and impact properties at +70 and –40 degrees F are of a constant value regardless of the austenitizing (quenching) temperature or the heating time prior to the quench.

2—The impact properties of the full quenched steel at –40 degrees F are but little below the values at +70 degrees F.

3—Impact values at –40 degrees F for the 3-inch section were below those of the 1-inch section but heating time prior to the quench was not important in changing the values.

4—A comparison of full quenching and interrupted quenching shows that for 1-inch material the room temperature impact properties are the same. However, at -40 degrees F testing temperature the values for interrupted quenching were much below those of a full quench. Also, as the time of heating at any one temperature increased the toughness values decreased.

5—The Ac_3 temperature of 1530 degrees F for this steel would indicate that the heating temperature should be about 1600 or 1650 degrees F whereas the holding time at temperature need not be more than 15 minutes. The microstructures showed (Figure 38) slight differences resulting from the effect of quenching temperature.

Mn-Cr-Mo—Effect of Time and Temperature Before Quenching

Homogenization heat treatment, employed in connection with the austenitizing (quenching) studies on the Mn-Cr-Mo cast steel, consisted of heating the castings to 1750 degrees F for 30 minutes and air cooling. Toughness and tensile values obtained after quenching the steel from various temperatures are given in Table 20.

The impact values are so close together that little can be shown by attempting to plot the results. The impact test data show the following trends:

1—Interrupted quenching produced slightly higher toughness values than were secured by full

TABLE 19

Mn-B Cast Steel: 1- and 3-inch Sections
Effect of Quenching Temperature, Time and Rate on the Mechanical Properties

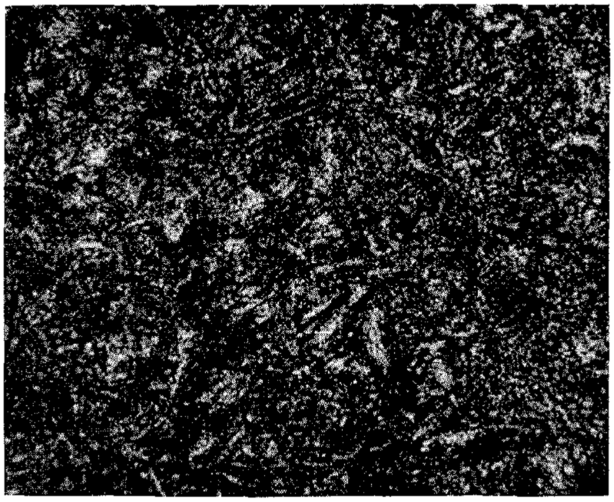
HEAT TREATMENT: Normalize—1650°F, 30 minutes, air cool

Harden—1550, 1650, 1750°F for 15, 30 and 90 minutes, water quench. Interrupted quench at 500°F for 60 seconds for 1-inch section and 240 seconds for 3-inch section, and return to quench.

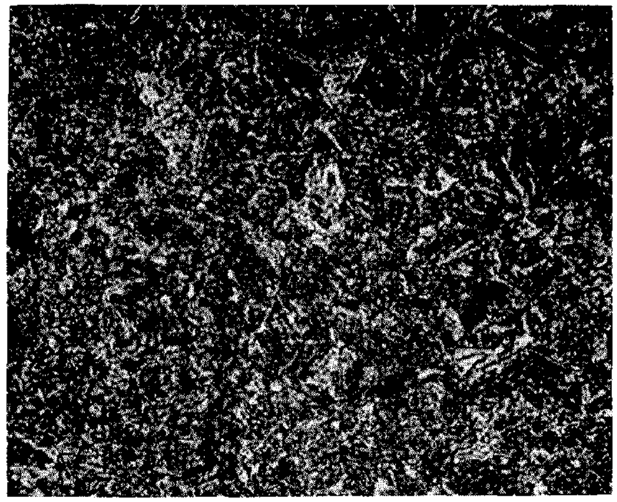
Temper—1200°F for 30 minutes, water quench

Heat Treatment				Charpy V-Notch Impact				
Quench °F	Time min.	Rate of Quench	BHN	1" Section +70°F	1" Section -40°F	3" Section +70°F	3" Section -40°F	BHN
	15	Full	241	37	30	56	26	207
		Interrupted	223	41	31	—	—	—
1550	30	Full	233	42	37	53	25	212
		Interrupted	229	37	29	—	—	—
	90	Full	235	34	35	51	29	197
		Interrupted	233	41	20	—	—	—
	15	Full	220	39	34			
		Interrupted	233	36	22			
1650	30	Full	229	38	37			
		Interrupted	223	43	29			
	90	Full	217	42	41			
		Interrupted	212	40	19			
	15	Full	229	39	34			
		Interrupted	212	36	30			
1750	30	Full	231	37	32			
		Interrupted	229	38	14			
	90	Full	220	37	35			
		Interrupted	229	32	8			

1-inch Section			BHN	T.S. 1000 psi	Y.P. 1000 psi	El. %	R.A. %
1550	30	Full	233	108.0	98.0	21	45.1
1650	30	Full	229	106.5	96.5	21	44.5
1750	30	Full	231	110.5	95.5	20	43.9
3-inch Section							
1550	15	Full	207	95.0	71.5	23	35.3



a. Heated to 1550°F 30 minutes full quench



b. Heated to 1550°F 30 minutes interrupted quench

c. Heated to 1750°F 30 minutes full quench

d. Heated to 1750°F 30 minutes interruped quench

Figure 38—Mn-B 1-inch Section. Effect of quenching temperature. Steel tempered at 1200 degrees F for 30 minutes. Etched 2% nital 500X

quenching. This is not consistent with other results. The reason for the improved values is probably the result of the lower hardness after the interrupted quench. The microstructures of the full and delayed quenched specimens after tempering are not too revealing as is shown in Figure 39.

2—Impact values at −80 degrees F especially at the higher heating temperatures, showed both ductile and brittle conditions, and a temperature of −80 degrees F is apparently the transition temperature.

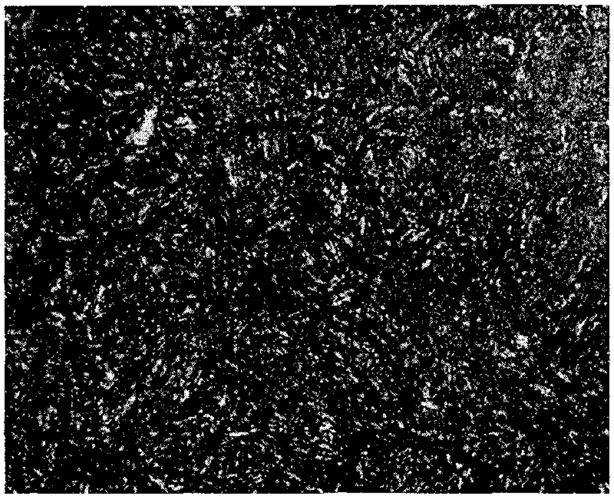
3—The temperature and time of heating prior to quenching were not significant as to benefaction of toughness properties.

4—Impact values for the 3-inch section fell off drastically at the low temperatures of −40 and −80 degrees F. The 70 degree F values were higher than obtained for the 1-inch section. The transition temperature for 3-inch section material is apparently in the region of −40 degrees F and accounts for the low impact values at the low testing temperatures.

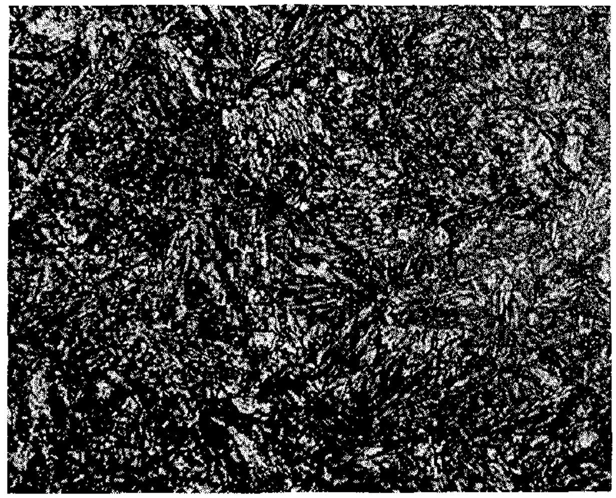
5—The hardness values were not as uniform as desired. Variations from 272 to 335 were obtained, and they undoubtedly reflected some variations in the impact values secured.

Cr-Mo—Austenitizing; Time, Temperature and Cooling Rates

The effect of conditions of quenching on the toughness and tensile properties of Cr-Mo cast steel was obtained at two hardness levels for the 1-inch section and for one hardness level for test speci-



a. Full quench



b. Interrupted quench

Figure 39—Mn-Cr-Mo 1-inch section. Effect of quenching rate. Heated 1650 degrees F 90 minutes; tempered 1125 degrees for 30 minutes. Nital 2% 500X

TABLE 20

Mn-Cr-Mo Cast Steel; 1- and 3-inch Sections Effect of Quenching Temperature, Time and Rate on the Mechanical Properties

HEAT TREATMENT: Normalize—1750°F, 30 minutes, air cool

Harden—1550, 1650, 1750°F for 15, 30 and 90 minutes, water quench. Interrupted quench at 500°F for 60 seconds in air, return to quench.

Temper—1125 degrees F for 30 minutes, water quench

Heat Treatment				Charpy V-Notch Impact						
Quench °F	Time min.	Rate of Quench	BHN	1" Section +70°F	1" Section −40°F	1" Section −80°F	3" Section +70°F	3" Section −40°F	3" Section −80°F	BHN
	15	Full	327	37	36	33	51	22	20	272
		Interrupted	308	46	41	40	—	—	—	
1550	30	Full	302	44	42	41	47	18	15	286
		Interrupted	288	49	47	48	—	—	—	
	90	Full	304	43	40	38	54	32	28	272
		Interrupted	321	38	40	37	—	—	—	
	15	Full	311	38	36	34				
		Interrupted	274	51	44	35				
1650	30	Full	323	35	32	22				
		Interrupted	299	44	42	32				
	90	Full	320	47	36	35				
		Interrupted	291	49	42	30				
	15	Full	306	43	43	35				
		Interrupted	296	45	45	44				
1750	30	Full	335	31	29	21				
		Interrupted	291	49	38	30				
	90	Full	327	36	30	21				
		Interrupted	321	41	29	15				

1-inch Section			BHN	T.S. 1000 psi	Y.P. 1000 psi	El. %	R.A. %
1550	15	Interrupted	308	144.0	135.2	11.5	25.8
1650	90	Full	320	143.7	132.5	15.0	34.3
1750	15	Interrupted	296	136.3	123.8	11.7	26.7
3-inch Section							
1550	90	Full	272	137.0	120.8	11.0	24.0

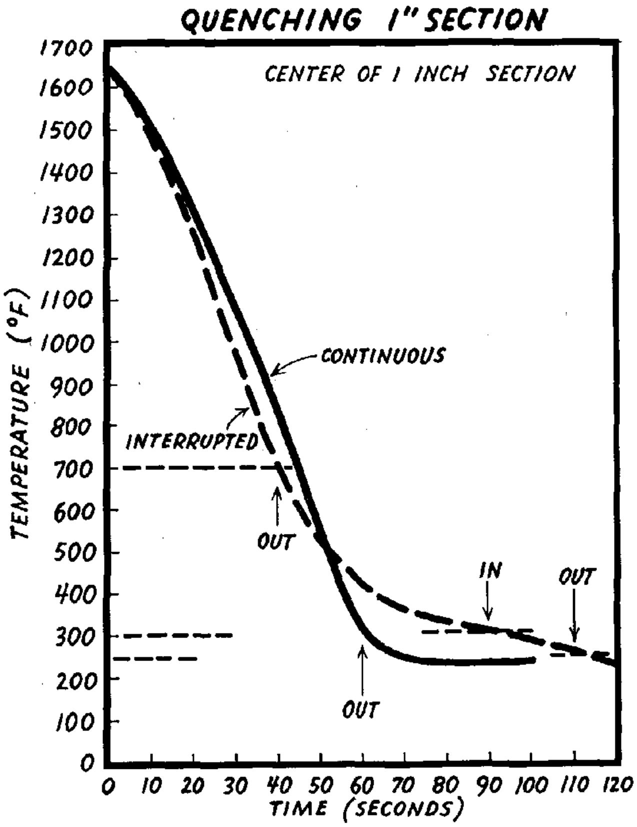


Figure 40—Full quench and interrupted quench curves for the center of 1-inch sections for Cr-Mo and Mn-Ni-Cr-Mo cast steels. Quenched in water from 1650°F. Interrupted quench; castings withdrawn when surface reached 700°F, held for 50 seconds in air and returned to the quench.

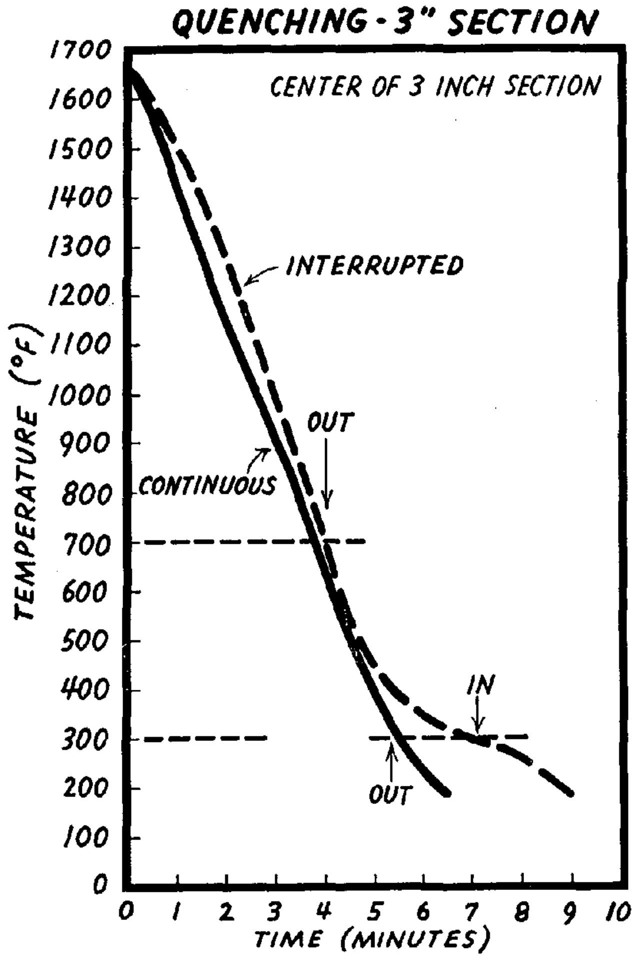


Figure 41—Full quench and interrupted quench curves for the center of 3-inch sections for Cr-Mo and Mn-Ni-Cr-Mo cast steels. Quenched in water from 1650°F. Interrupted quench; castings withdarwn when surface reached 700°F, held for 3.1 minutes in air and returned to the quench.

mens taken from the 3- and 6-inch section. The cooling curves obtained by quenching the 1-, 3- and 6-inch sections both by a full quench and by an interrupted quench are shown in Figures 40, 41 and 42. The interrupted quench specified that the castings be removed from the water when the skin temperature reached 700 degrees F and held in air until the section equalized at temperature before continuing with the quench. The values obtained, employing three austenitizing (quenching) temperatures, three heating times prior to quenching, and two quenching rates, are given in Tables 21 and 22.

An examination of the toughness values of Table 21 and the graphs of Figure 43 would indicate that the interrupted quench produced impact values similar to those obtained by a full drastic quench and that a variation in hardness level also produced similar results.

Graphs of all the impact test results were made, Figures 44 to 47 inclusive, to illustrate the effectiveness of the impact testing temperature on the test values. Also, a graphic comparison can be made of: (a) full vs. interrupted quenching, (b) low vs. high austenitizing temperature, and (c) short vs. long heating times prior to the quench. It should be pointed out that the test points were joined by straight lines for clarity purposes. In most cases the trend line should be drawn through an average of the points because the data and the curves indicate that heat time at the various temperatures is not a variable to be given serious or careful consideration.

The only case where time of heating prior to quenching is significant is shown in Figures 46 and 47 for 15 minute heating times at 1550 degrees F. The Ac_3 temperature of the Cr-Mo steel is 1600 degrees F, and the short heating time may have been started before the heavy sections had reached the heating temperature selected. It is evident that the temperature to be employed prior to quenching for this steel is 1650 degrees F. At this temperature a very short heating time of 15 minutes is quite sufficient prior to quenching even for heavy section castings.

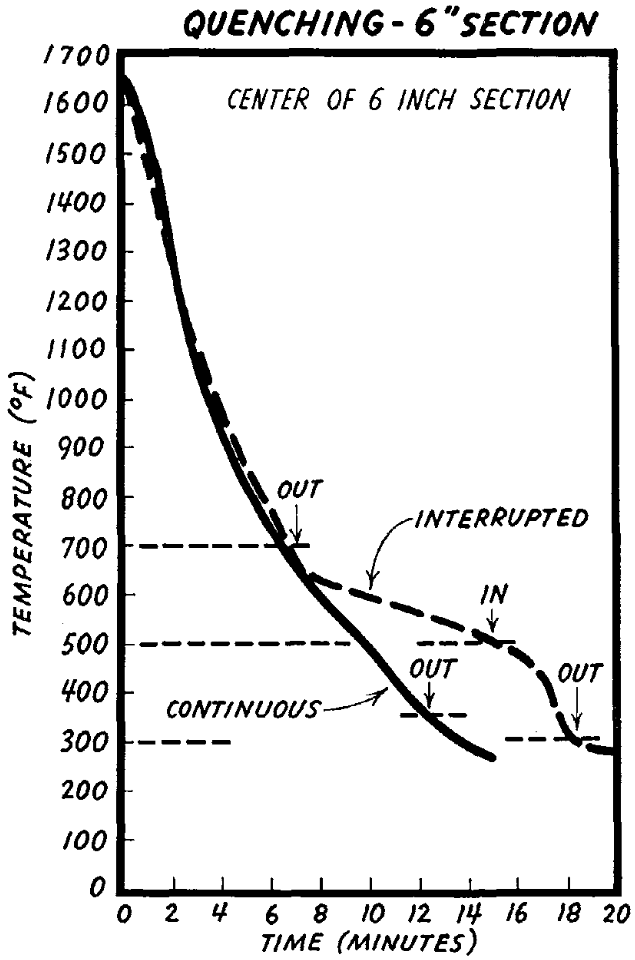


Figure 42—Full quench and interrupted quench curves for the center of 6-inch sections for Cr-Mo and Mn-Ni-Cr-Mo cast steels. Quenched in water from 1650°F. Interrupted quench; castings withdrawn when surface reached 700°F, held for 8 minutes in air and returned to the quench.

The tensile strength values are very consistent regardless of austenitizing temperature or time or rate of quenching. The tempered hardness is the most important single factor in the variation of these properties.

The results secured from the test data for the Cr-Mo steel can be summarized as follows:

1—A short 15 minute heating time at the low austenitizing temperature of 1550 degrees F prior to quenching, is not sufficient to produce the highest toughness values in heavy 3- and 6-inch sections.

2—Otherwise, there is no effective pattern of improvement through varying the austenitizing temperature or time prior to quenching.

3—A temperature of 1650 degrees F for 15 minutes produces high toughness values for casting sections of 1 to 6 inches.

4—Impact values secured with an interrupted quench were equal to those obtained by the employment of a full quench. The technique employed provided the desired "as-quenched" hardness level on final quenching.

5—A plot of impact values for the three section thicknesses at a constant Brinell hardness value (Figure 48) shows that section size makes little difference in this relationship. The 1-inch section values are somewhat erratic in character and presumably a flat curve could be drawn which would closely parallel the 3-

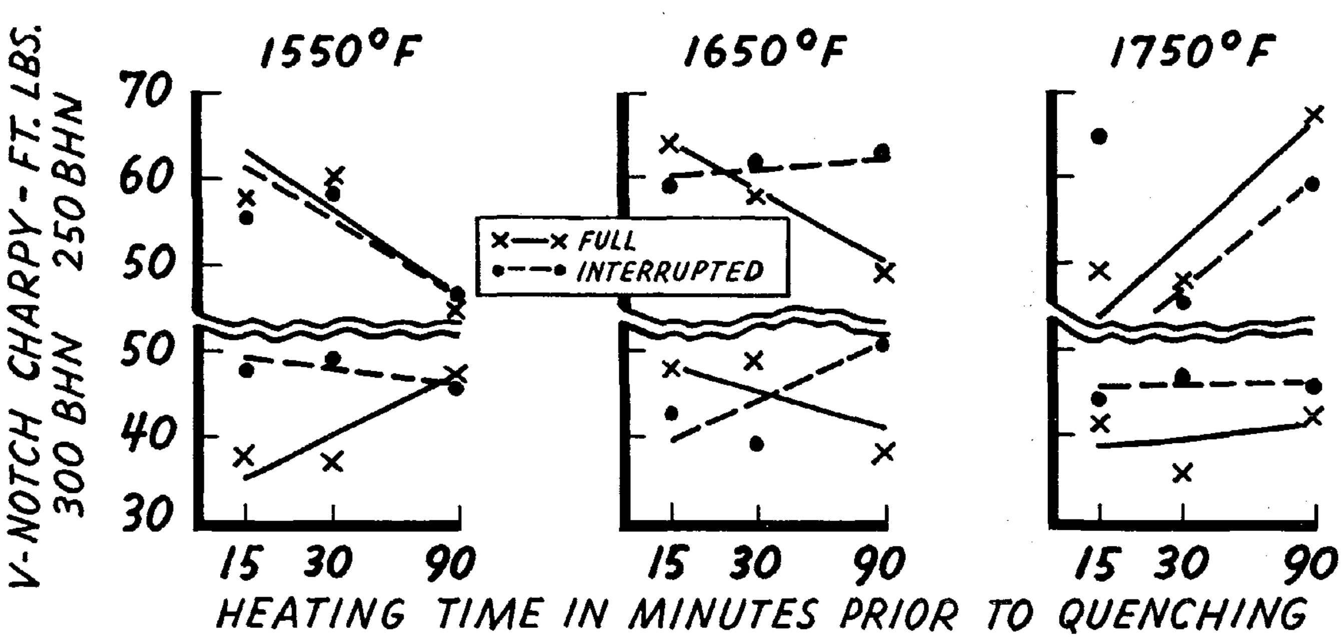


Figure 43—The effect of heating temperature (austenitizing) and the time of heating prior to quenching on the toughness properties of Cr-Mo cast steel, 1-inch thickness, tempered to 250 and 300 BHN. Homogenized at 1650 degrees F, tested at —40 degrees F

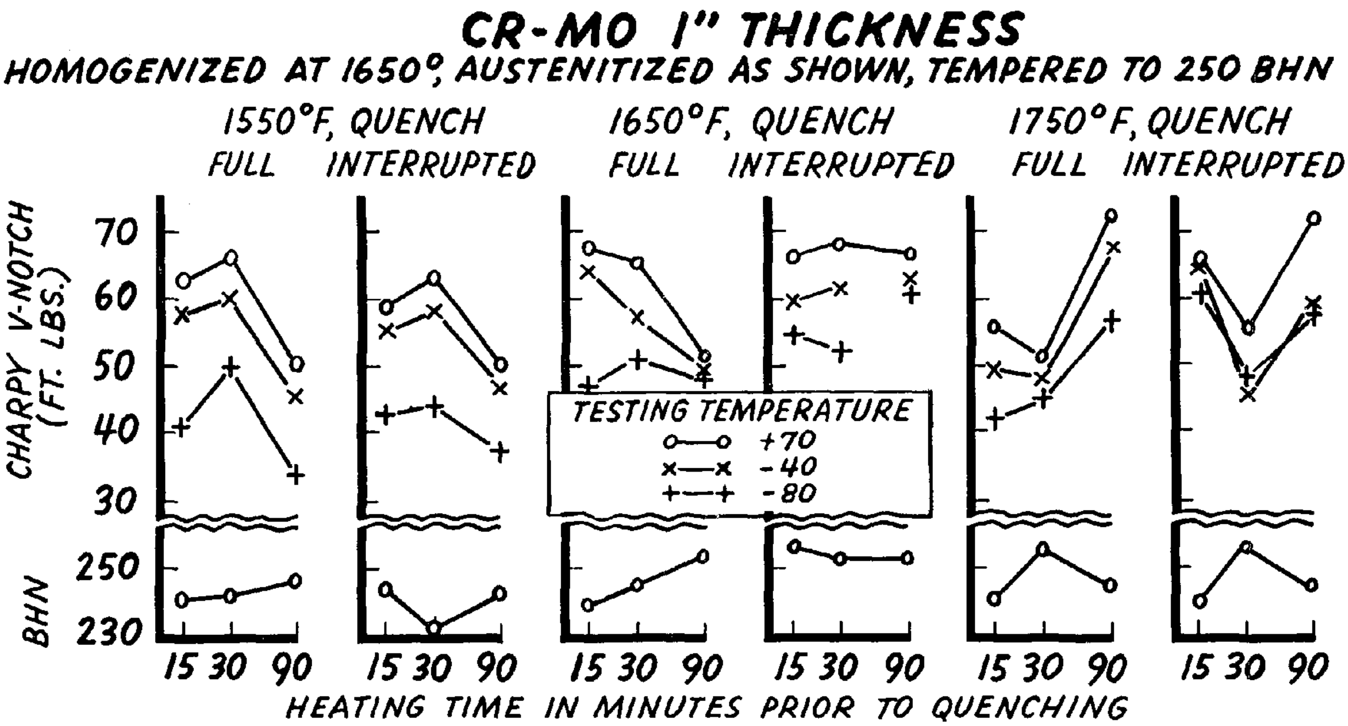


Figure 44—Cr-Mo 1-inch section. The effect of heating temperature and time prior to quenching on the impact properties of full and interrupted, quenched and tempered (250 BHN) steel.

TABLE 21
Cr-Mo Cast Steel; 1-inch Section Effect of Quenching Temperature, Time and Rate on the Mechanical Properties

HEAT TREATMENT: Normalize—1650°F, 15 minutes, air cool
Harden—1550, 1650, 1750°F for 15, 30 and 90 minutes, water quench. Interrupted quench at 700°F for 60 seconds in air, return to quench.
Temper—1150°F for 30 minutes (300 BHN) and 1250°F for 2 hours (250 BHN), water quench.

Heat Treatment			Charpy V-Notch Impact ft-lbs							
Quench °F	Time min.	Rate of Quench	BHN	1" Section (250 BHN) +70°F	1" Section (250 BHN) −40°F	1" Section (250 BHN) −80°F	BHN	1" Section (300 BHN) +70°F	1" Section (300 BHN) −40°F	1" Section (300 BHN) −80°F
	15	Full	240	63	56	41	284	42	37	30
		Interrupted	243	59	56	43	286	53	48	38
1550	30	Full	242	66	60	50	300	39	37	32
		Interrupted	232	63	58	44	302	50	49	41
	90	Full	246	50	45	33	308	48	47	37
		Interrupted	243	50	46	37	296	48	46	38
	15	Full	238	67	64	47	312	50	48	42
		Interrupted	256	66	59	54	310	48	43	47
1650	30	Full	245	66	58	51	296	52	49	40
		Interrupted	253	68	61	52	294	41	39	39
	90	Full	254	51	50	48	292	41	38	37
		Interrupted	253	67	63	61	300	54	51	58
	15	Full	241	56	49	42	292	44	40	32
		Interrupted	240	66	65	61	293	51	45	33
1750	30	Full	256	51	48	44	296	41	36	24
		Interrupted	256	55	46	48	296	51	47	33
	90	Full	245	72	67	56	306	44	42	41
		Interrupted	244	72	59	59	295	43	41	33

Quen. °F	Time min.	Rate of Quen.	BHN	T. S. 1000 psi	Y. S. 1000 psi	El. %	R.A. %	BHN	T. S. 1000 psi	Y. S. 1000 psi	El. %	R.A. %	Time min.
1550	30	Full	234	110.1	93.5	22.2	57.2	316	144.8	121.2	13.7	41.6	90
		Inter.	243	116.6	94.4	17.0	48.8	294	140.2	118.5	16.0	47.0	15
1650	15	Full	248	116.9	95.2	16.3	42.6	321	143.5	119.0	11.8	34.1	30
		Inter.	255	116.7	92.4	17.5	46.4	306	140.3	118.8	17.2	49.4	90
1750	90	Full	247	108.4	93.1	19.7	54.0	302	147.4	122.5	12.5	39.5	30
	15	Inter.	238	113.6	94.1	19.0	54.2	321	140.0	118.0	13.8	45.9	15

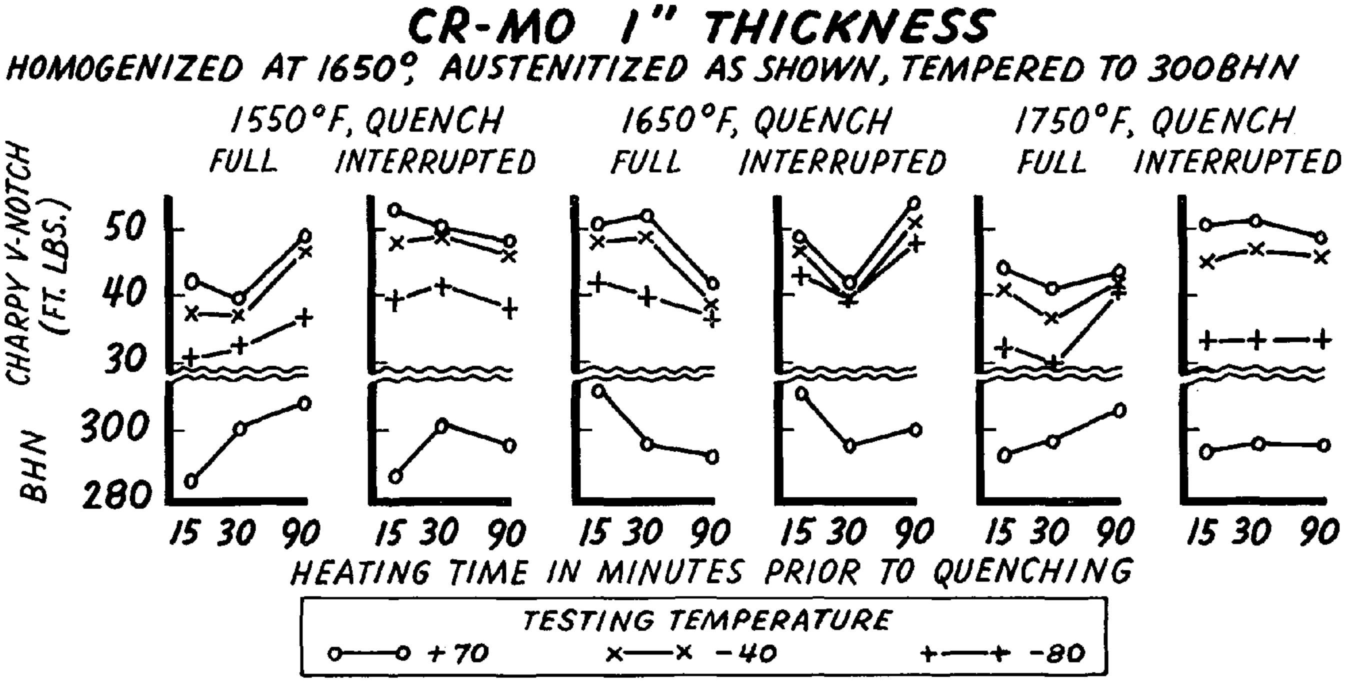


Figure 45—Cr-Mo 1-inch section. The effect of heating temperature and time prior to quenching on the impact properties of full and interrupted, quenched and tempered (300 BHN) steel.

TABLE 22

Cr-Mo Cast Steel; 3- and 6-inch Sections Effect of Quenching Temperature, Time and Rate on the Mechanical Properties

HEAT TREATMENT: Normalize—1650°F, 15 minutes, air cool
Harden—1550, 1650, 1750°F for 15, 30 and 90 minutes, water quench. Interrupted quench at 700°F for 3.1 (3") and 8 (6") minutes in air, return to the quench
Temper—1250°F for 30 minutes (250 BHN), water quench

Heat Treatment			Charpy V-Notch Impact ft-lbs							
Quench °F	Time min.	Rate of Quench	BHN	3" Section +70°F	3" Section –40°F	3" Section –80°F	BHN	6" Section +70°F	6" Section –40°F	6" Section –80°F
	15	Full	248	56	30	17	246	62	44	44
		Interrupted	251	50	33	19	261	58	27	22
1550	30	Full	251	58	47	38	256	58	56	43
		Interrupted	256	52	43	31	268	71	65	41
	90	Full	267	62	51	50	258	76	68	67
		Interrupted	265	49	46	43	270	73	71	68
	15	Full	267	60	48	47	261	64	57	53
		Interrupted	259	62	55	42	269	68	67	64
1650	30	Full	262	53	49	42	264	62	56	49
		Interrupted	261	51	50	46	267	66	62	53
	90	Full	259	55	50	47	264	70	64	64
		Interrupted	261	57	54	47	261	78	73	65
	15	Full	260	61	51	48	264	63	53	36
		Interrupted	272	49	46	40	260	64	59	47
1750	30	Full	256	63	53	46	258	62	58	43
		Interrupted	257	58	52	53	258	63	60	43
	90	Full	256	61	51	56	255	59	53	32
		Interrupted	257	48	47	43	256	61	55	34

			3-inch Section					6-inch Section					
Quen. °F	Time min.	Rate of Quen.	BHN	T. S. 1000 psi	Y. S. 1000 psi	El. %	R.A. %	BHN	T. S. 1000 psi	Y. S. 1000 psi	El. %	R.A. %	Time min.
1550	90	Full	277	127.5	109.1	11.0	22.5	262	116.1	92.1	15.2	41.4	90
	90	Inter.	286	131.7	113.0	11.0	23.6	265	117.3	97.4	14.0	35.0	90
1650	90	Full	286	130.1	112.4	7.5	19.2	269	125.5	93.0	13.7	31.4	90
	15	Inter.	273	132.7	114.3	8.0	20.5	269	126.3	94.8	11.0	28.2	15
1750	30	Full	281	131.3	113.6	8.0	18.7	269	120.4	91.0	14.0	30.3	30
	30	Inter.	269	127.6	109.3	14.3	38.6	258	122.3	91.8	16.3	41.0	30

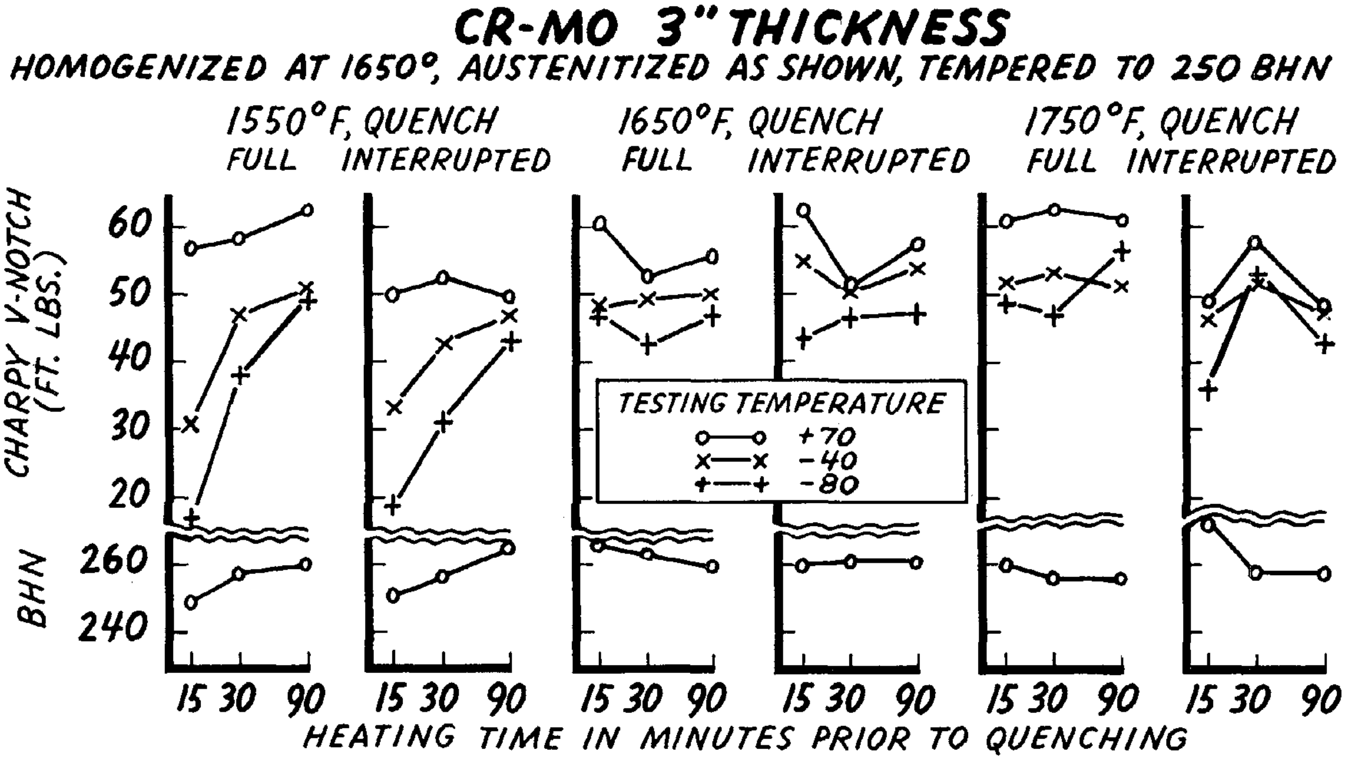


Figure 46—Cr-Mo 3-inch section. The effect of heating temperature and time prior to quenching on the impact properties of full and interrupted, quenched and tempered (250 BHN) steel.

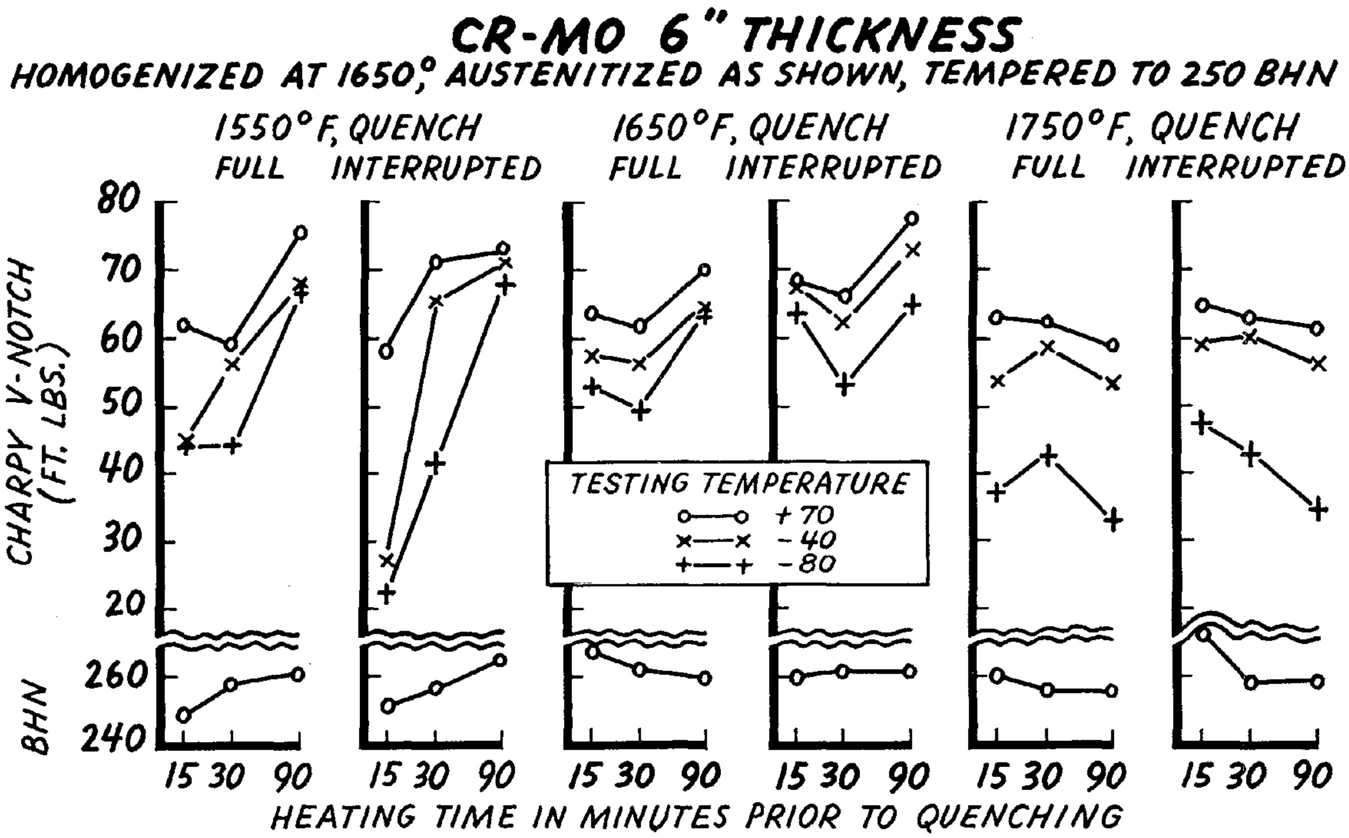


Figure 47—Cr-Mo 6-inch section. The effect of heating temperature and time prior to quenching on the impact properties of full and interrupted, quenched and tempered (250 BHN) steel.

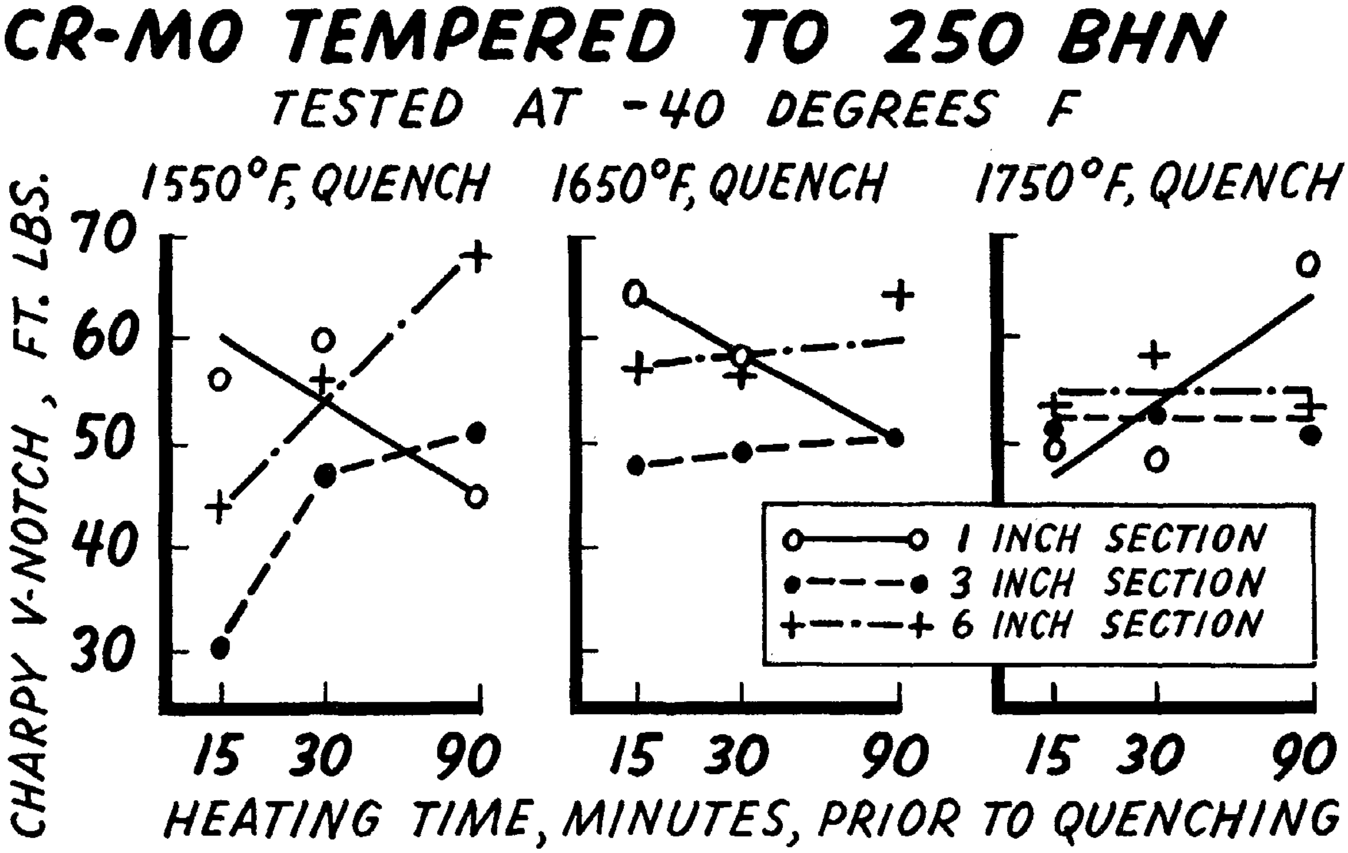


Figure 48—The effect of section size on the −40°F impact properties of Cr-Mo cast steel heated at various temperatures and times prior to a full quench and tempered at 250 Brinell hardness.

and 6-inch section values. It is interesting to note how comparable the values are, especially since the quenching time for the sections was considerably different (2 minutes for 1-inch section and 16 minutes for 6-inch section). However, it should be noted that Cr-Mo steel has a high hardenability which permits transformation to satisfactory toughness after quenching sections as thick as 6 inches.

6—The microstructures for all section thicknesses and austenitizing temperatures and times were very similar in character. Figure 49 shows the one heating temperature of 1650 degrees F with varying section thicknesses for the two quenching rates.

Mn-Ni-Cr-Mo—Austenitizing: Time, Temperature and Cooling Rates

The Mn-Ni-Cr-Mo cast steel was studied at only one section thickness (3 inches) and at one hardness level (250 BHN). Heating temperatures and times prior to quenching were the same as previously employed for the other steels studied.

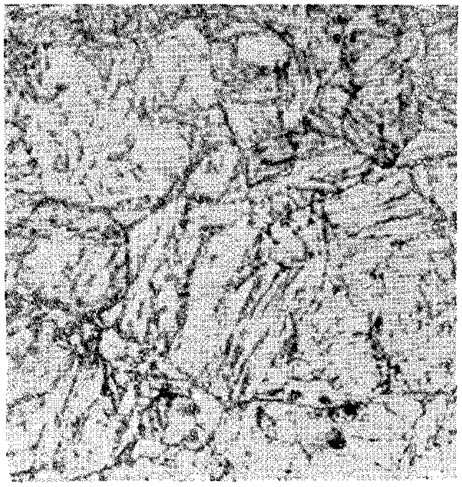
The toughness values obtained by using a full and interrupted quench are given in Table 23. There is not sufficient variation in the values to plot them. The only thing that can be said is that some of the 15-minute heating time values at 1550 degrees F are a little on the low side. Otherwise, neither the temperature of quenching nor the heating time prior to the quench had a pronounced influence on the toughness properties. The values obtained on interrupted quenching were equivalent to those obtained by the employment of a full quench.

The microstructures are the same for both full and interrupted quench regardless of heating time or quenching temperature. A set of these microstructures is illustrated in Figure 50. It will be observed the manner in which the zepherin chloride etch brings out the grain boundary conditions in a quenched and tempered steel. This pronounced grain boundary condition may be associated with the relatively low values exhibited in the Charpy V-notch impact test.

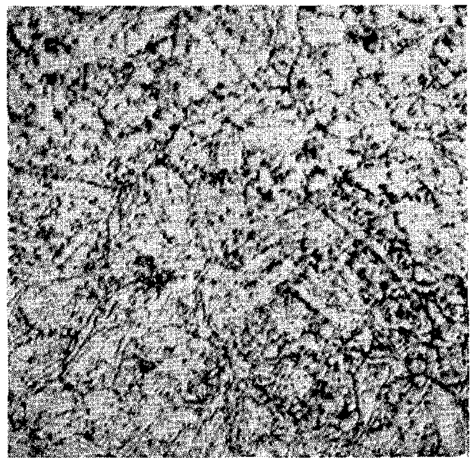
Summary on Austenitizing Temperature and Time

The effect of heating time and the temperature of heating prior to quenching on the toughness and

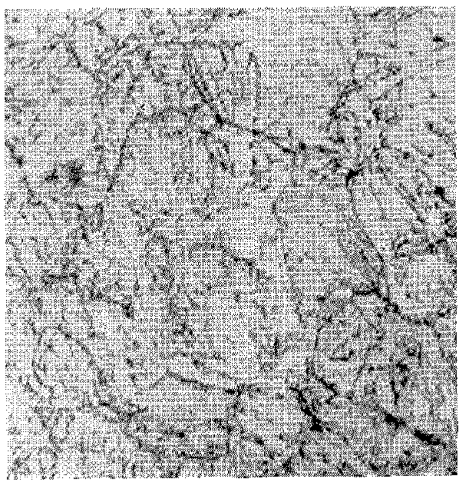
Interrupted quench *Full quench*



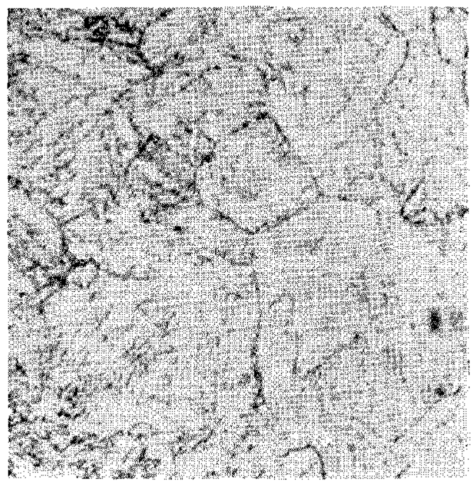
a. One (1) inch section



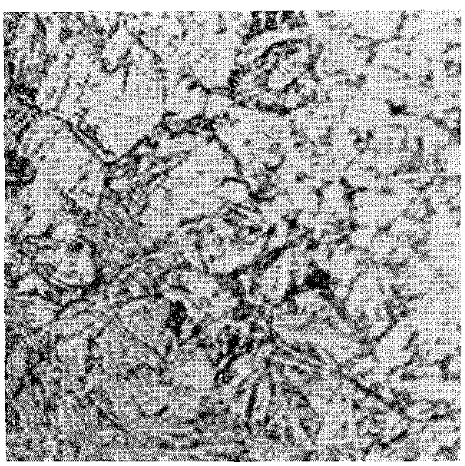
b. One (1) inch section



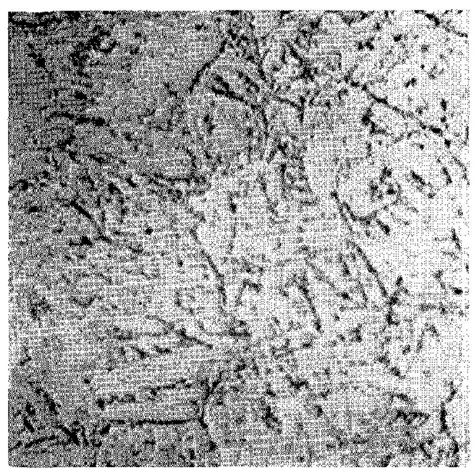
c. Three (3) inch section



d. Three (3) inch section



e. Six (6) inch section



f. Six (6) inch section

Figure 49—Microstructure of Cr-Mo cast steel, homogenized 1650 degrees 15 minutes. Austenitized 1650 degrees, 30 minutes, water quenched and tempered to 250 Brinell Hardness (1250°F 30 minutes) zepherin chloride etch. 1000X

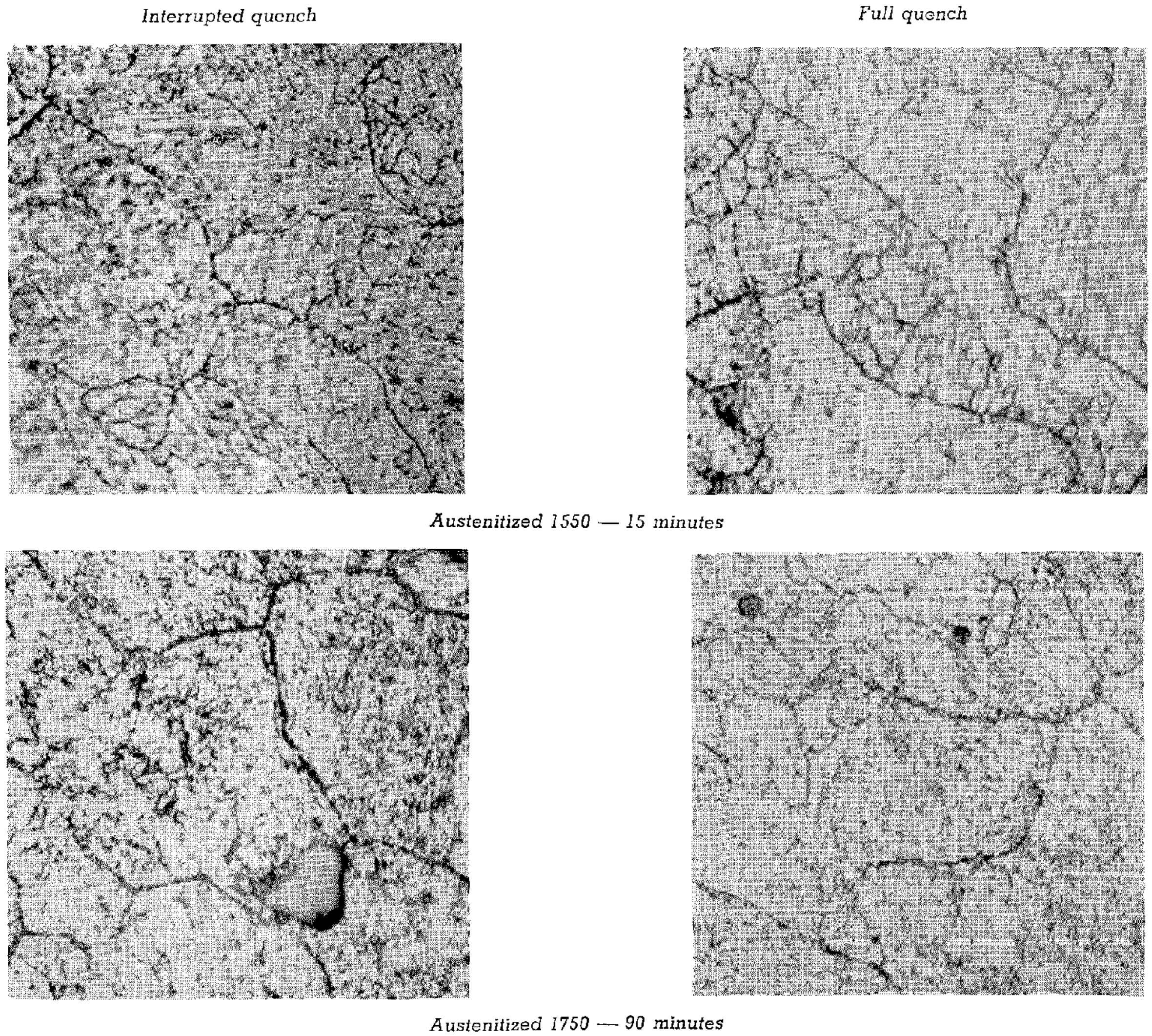


Figure 50—Microstructure of Mn-Ni-Cr-Mo cast steel, homogenized 1650 degrees F for 60 minutes. Austenitized for the conditions shown, water quenched and tempered at 1250 degrees F for 30 minutes. Zepherin chloride etch. 1000X. N.B. This condition was characteristic of heats Mn-Ni-Cr-Mo #1, #2 and #3 but not of heat #4. (See Section IX)

strength properties of quenched and tempered cast steels can be summarized as follows:

1—The heating temperature selected prior to quenching has little effect on the toughness properties of quenched and tempered cast steel. It is generally advisable that a temperature about 50 to 100 degrees above the Ac_3 point be used. This means that for most cast steels a temperature of 1600 to 1650 degrees F would be selected. The steels studied in this research had Ac_3 temperatures between 1500 and 1580 degrees F. Therefore, a temperature of 1600 degrees F would constitute the best single temperature to employ.

2—There is no advantage in prolonging the heating time at the selected temperature prior to quenching. A time period of 15 minutes, after the casting is heated throughout, is ample to secure optimum properties, regardless of the section thickness. However, for plant heat treating operations it is probable that a period of 30 minutes will be employed although there is no advantage gained by heating past the 15-minute period.

3—The interrupted quench produces no consistent differences as compared to the full quench, provided the desired as-quenched hardness level is obtained. The variations noted consisted of the low impact values for the Mn-B steel at −40 degrees F and slightly higher values secured for the Mn-Mo cast steel.

It will be recalled that the test blocks were drastically quenched to a skin temperature of 500 degrees

TABLE 23

Mn-Ni-Cr-Mo Cast Steel; 3-inch Section
Effect of Quenching Temperature, Time and Rate on the Mechanical Properties

HEAT TREATMENT: Normalize—1650°F, 60 minutes, air cool
Harden—1550, 1650, 1750°F for 15, 30 and 90 minutes. Water quench. Interrupted quench at 700°F for 3.1 minutes in air, return to the quench.
Temper—1250°F, 30 minutes (250 BHN), Water quench.

Heat Treatment			BHN	Charpy V-Notch Impact ft-lbs 3-Inch Section		
Quench °F	Time min.	Rate of Quench		+70°F	-40°F	-80°F
	15	Full	244	31	18	13
		Interrupted	244	25	17	12
1550	30	Full	245	31	15	15
		Interrupted	247	31	18	16
	90	Full	250	27	16	14
		Interrupted	244	29	19	16
	15	Full	259	29	17	15
		Interrupted	254	26	17	16
1650	30	Full	263	32	17	14
		Interrupted	254	37	22	17
	90	Full	256	32	25	21
		Interrupted	264	31	21	17
	15	Full	258	33	22	17
		Interrupted	258	28	23	23
1750	30	Full	257	37	22	18
		Interrupted	262	32	20	17
	90	Full	251	30	18	16
		Interrupted	253	43	26	25

			BHN	Tensile Strength 1000 psi	Yield Strength 1000 psi	Elon. %	R. A. %
1550	15	Full	269	125.8	108.1	8.3	17.9
	90	Interrupted	269	124.5	106.9	7.8	19.8
1650	90	Full	286	121.3	105.8	6.8	17.2
	90	Interrupted	282	124.3	105.8	8.3	15.7
1750	30	Full	286	122.9	105.8	7.0	16.9
	90	Interrupted	277	126.5	106.9	7.3	18.5

F and that they were allowed to equalize in air and then again quenched. A critical part of the quenching operation lies in quenching drastically at the M_s temperature (400 degrees F, or thereabouts). The result is that the microstructures of the full and interrupted quenched steels are similar and, in the final analysis, the rate of quenching at the lower temperature is the same. This condition was not the case for the carbon steel when quenching conditions through the entire temperature scale varied with water vs. oil quenching. In this case the rate of quenching was not important in governing the resultant mechanical properties.

SECTION VII

THE IMPORTANCE OF THE DOUBLE QUENCH ON TOUGHNESS

Statements have been made from time to time in the technical literature that by employing a double quenching treatment it is possible to improve the toughness properties of carbon and low-alloy cast steels. However, there has been some confusion regarding the true value of a double quenching treatment because often a constant hardness level is not obtained.

It is observed in Section VI that there is no need to go to high heating temperatures prior to quenching; therefore, the double quench would be employed from the same temperature or about the same temperature.

The studies encompassed all of the steels reported previously for various section sizes. In all cases a normalizing treatment was employed prior to the first quenching treatment and the second quench followed the first with a tempering treatment to a definite hardness level being the final treatment.

Carbon Steel—Double Quench

The carbon steel was double quenched from 1600 degrees F. This temperature was selected as it was the lowest temperature that could produce high values in the shortest time. However, heating times were held to 30 minutes. The values obtained by the double quench heat treatment are listed in Table 24.

The improvement in impact strength at –40 degrees F may not be significant, statistically; however, it is a 25 percent increase and, therefore, it should be indicated that the double quenching produces better impact properties than a single quenching treatment for carbon steel.

Mn-B. Double Quench

The quenching temperature selected was 1550 degrees F with a heating time of 30 minutes. The results obtained are listed in Table 25.

TABLE 24

Carbon Cast Steel. Effect of Double Quenching on the Mechanical Properties of 1-inch Sections

HEAT TREATMENT: Homogenize—1650°F 30 minutes, air cool
Harden—1600°F, 30 minutes, water quench
Temper—1150°F, 30 minutes (200 Brinell)

Properties	Single Quench	Double Quench
Charpy V-Notch, 70°F, ft-lbs	54	57
Charpy V-Notch, –40°F, ft-lbs	32	40
Brinell Hardness No.	200	200
Tensile Strength, 1000 psi	94.4	95.9
Yield, 1000 psi	69.0	70.7
Elongation in 2 in., %	25.8	25.7
Reduction of Area, %	56.4	57.9

TABLE 25

Mn-B Cast Steel. Effect of Double Quenching on the Mechanical Properties of 1- and 3-inch Sections

HEAT TREATMENT: Homogenize—1650°F, 15 minutes, air cool
Harden—1550°F, 30 minutes, water quench
Temper—1200°F, 30 minutes, water quench

	1-inch		3-inch	
Properties	Single Quench	Double Quench	Single Quench	Double Quench
Impact 70°F ft-lbs	42	38	53	50
Impact –40°F ft-lbs	37	26	25	17
Brinell Hardness No.	233	231	212	209
Tensile Strength, 1000 psi	108.0	110.0	95.0	108.0
Yield, 1000 psi	98.0	96.0	71.5	92.5
Elongation %	21.0	20.0	23.0	20.0
Reduction of Area %	45.1	40.3	35.3	41.2

Observations that can be made from the table are that: (1) the double quench did not improve the impact values in either the 1- or 3-inch sections. There is some doubt as to the tensile values. The 3-inch section double quench tensile values appear high for the corresponding hardness; (2) it is interesting to observe the wide spread of impact values at –40 degrees F for this steel. Apparently the transition curve is nearly vertical at this temperature.

Mn-Cr-Mo Cast Steel. Double Quench

The effect of the double quench on the properties of 1- and 3-inch sections of Mn-Cr-Mo cast steel is given in Table 26. A review of the table indicates that: (1) a direct comparison between the single quench and the double quench for the 1-inch section cannot be made because of the difference in hardness level; (2) the 3-inch section results are comparable and the double quench improve the impact properties tremendously. However, this excessive variation may be questionable as the single quench, 3-inch section values seem unduly low; (3) apparently the tensile properties are not improved by the double quench.

Cr-Mo. Double Quench

The Cr-Mo steel was studied for 1-, 3-, and 6-inch section sizes under one condition of heat treatment. The results obtained are given in Table 27.

A comparison of the single and double quench values in Table 27 would indicate that: (1) the double quench was not a factor in materially improving the impact properties of the Cr-Mo cast steel. In practically all cases there was a slight improvement of a few foot-pounds, but statistically the values may not be important; (2) values for the

TABLE 26

Mn-Cr-Mo Cast Steel. Effect of Double Quenching on the Mechanical Properties of 1- and 3-inch Sections

HEAT TREATMENT: Homogenize—1750°F, 30 minutes, air cool
Harden—1550°F, 15 minutes, water quench
Temper—1125°F, 30 minutes, water quench

	1-inch		3-inch	
Properties	Single Quench	Double Quench	Single Quench	Double Quench
Impact 70°F, ft-lbs	37	31	51	56
Impact –40°F, ft-lbs	36	21	22	46
Impact –80°F, ft-lbs	33	20	20	32
Brinell Hardness No.	327	352	272	269
Tensile Strength, 1000 psi	144.0	156.8	137.0	130.2
Yield, 1000 psi	135.2	149.2	120.8	115.2
Elongation %	11.5	9.0	11.0	14.0
Reduction of Area %	25.8	13.8	24.0	27.6

3-inch sections are somewhat below those for the 1- and 6-inch sections.

Mn-Ni-Cr-Mo. Double Quench

High temperature heating was used for both the homogenization and hardening treatments because of the grain boundry films as shown by the zephiran chloride etch. The mechanical properties obtained are listed in Table 28.

It may be concluded from the data that: (1) there is no advantage in using a double quench treatment to improve the mechanical properties of this steel; (2) the erratic nature of the reduction of area values is probably a reflection of the influence of the grain boundary films; (3) two sets of widely divergent impact values were recorded for the same test conditions but made at entirely different times; (4) the impact properties improved as the section increased from 1- to 3- to 6-inch sections.

Summary of the Value of the Double Quench

Double quenching increases the time of heat treatment and the cost of the entire heat treating operation; therefore, it probably should not be recommended or carried on commercially unless there would be a definite improvement in the quality of the product. In view of this situation, the following summary can be made of the effectiveness of the double quenching heat treatment:

1—Microstructure studies of all the steels in the research program showed no change in the microstructures of the double quench specimens as compared to the single quench specimens.

2—There is no consistent record regarding the improvement of impact or tensile properties of carbon or low-alloy cast steels by employing a double quenching treatment.

TABLE 27

Cr-Mo Cast Steel. Effect of Double Quenching on the Mechanical Properties of 1-, 3-, and 6-inch Sections

HEAT TREATMENT: Homogenize—1650°F, 15 minutes, air cool
Harden—1650°F, 30 minutes, water quench
Temper—1250°F, 30 minutes, water quench

Properties	1-inch		3-inch		6-inch	
	Single Quench	Double Quench	Single Quench	Double Quench	Single Quench	Double Quench
Charpy V-Notch Impact						
70°F, ft-lbs	66	69	53	56	62	62
–40°F, ft-lbs	58	66	49	47	56	60
–80°F, ft-lbs	51	60	42	42	49	51
Brinell Hardness No.	245	255	262	268	264	268
Tensile Strength, 1000 psi	116.9	120.7		128.8		120.2
Yield, 1000 psi	95.2	99.5		107.5		97.8
Elongation %	16.3	16.5		14.5		17.2
Reduction of Area %	42.6	50.1		45.5		50.5

TABLE 28

Mn-Ni-Cr-Mo Cast Steel. Effect of Double Quenching on the Mechanical Properties of 1-, 3-, 6-inch Sections

HEAT TREATMENT: Homogenize—1750°F, 60 minutes, air cool
Harden—1750°F, 15 minutes, water quench
Temper—1250°F, 30 minutes, water quench

Properties	1-inch		3-inch		6-inch	
	Single Quench	Double Quench	Single Quench	Double Quench	Single Quench	Double Quench
Charpy V-Notch Impact						
70°F, ft-lbs	34	34	44	43	50	48
–40°F, ft-lbs	27	23	34	33	45	46
–80°F, ft-lbs	23	16	23	26	44	43
Brinell Hardness No.	269	255	266	261	268	264
Tensile Strength, 1000 psi	125.1	121.3	123.1	118.2	117.8	122.9
Yield, 1000 psi	105.3	101.6	103.6	102.1	96.8	104.2
Elongation %	15.5	13.0	14.7	11.3	13.2	14.5
Reduction of Area %	43.0	30.8	38.0	22.4	27.9	41.3

SECTION VIII

THE EFFECT OF TEMPERING TEMPERATURE AND TIME ON TOUGHNESS (VARIABLE HARDNESS)

The desired goal of commercial heat treating is to secure conditions commensurate with excellent properties in the shortest time possible. Short time heat treatments, therefore, would infer, on a cost basis, the use of the lowest temperature possible and the shortest heating time, with the elimination of as many extra step heat treatments as possible.

The tempering treatment is one wherein the tempering temperature has a great influence on the resultant properties of fully hardened steel. The highest toughness values are obtained at the highest tempering temperatures. Thus, the tempering temperatures must be just below the critical range if high toughness values are desired. However, toughness is usually not the only property value specified; tensile strength (hardness) being of equal or of greater significance. Consideration, therefore, must be given to the property of toughness at various hardness levels.

Steel is held at the tempering temperature for various periods of time because of a number of reasons. The literature of heat treatment claims the following reasons:

1—The time must be sufficiently long to permit the steel to attain a uniform temperature.

2—The thicker the steel part, the longer the time that the steel remains at the tempering temperature.

3—Steel castings must be slowly heated to the tempering temperature.

4—The longer the steel is tempered the more improved are the impact and ductility properties.

The above 4 points would indicate that long tempering times be employed. However, since short time heat treatments are of great concern in these studies it was deemed advisable that short tempering times would also be applied.

Tempering Procedure

Legs from keel blocks, 1 x 4 inch cross section 3-inch blocks and 6-inch block coupons were employed. These coupons were quenched in water and then heated to the tempering temperature selected to produce the desired hardness. After the coupons reached the tempering temperature, the time for holding at this temperature was started. Holding times of 15, 30, 90 and 320 minutes (300 in some cases) were given to separate coupons and then the coupons were water quenched.

The tempering studies were carried on in two groups: (1) test specimens which received a homogenization heat treatment prior to heating for the quench, and (2) no homogenization treatment before the quench heat treatment.

Heat Transfer Curves

Heating curves were obtained with thermocouples located on the surface and at the center of the test coupons. Curves were prepared for each section size studied for two conditions of heating: (a) slow heating of the sections by placing the coupon in a cold furnace and heating the coupon to the tempering temperature; (b) fast heating of the sections by placing the coupons in a furnace that was maintained at the tempering temperature.

The three research laboratories employed different types and sizes of furnaces; therefore, the heating rates are different. The heat transfer curves for the three agencies for various section sizes and rates of heating are shown in Figures 51 to 54.

The heat transfer curves indicate the following:

1—The temperature gradients in heating to the tempering temperature are, in general, small, regardless of the size of the furnace and the speed of heating.

2—The temperature gradient increases as the section thickness increases but even for a 6-inch section the gradient is not more than about 100 degrees F.

3—Cold castings can be placed into a hot furnace at the tempering temperature with only small temperature gradients resulting between the surface and center of the section.

Tempering of Carbon Cast Steels

The carbon cast steel was studied in the 1-inch section, both with and without a preheat treatment consisting of homogenizing at 1650 degrees F for 2 hours. Four tempering temperatures and four tempering times were employed. The results of the impact and tensile testing are given in Table 29 and Figure 55.

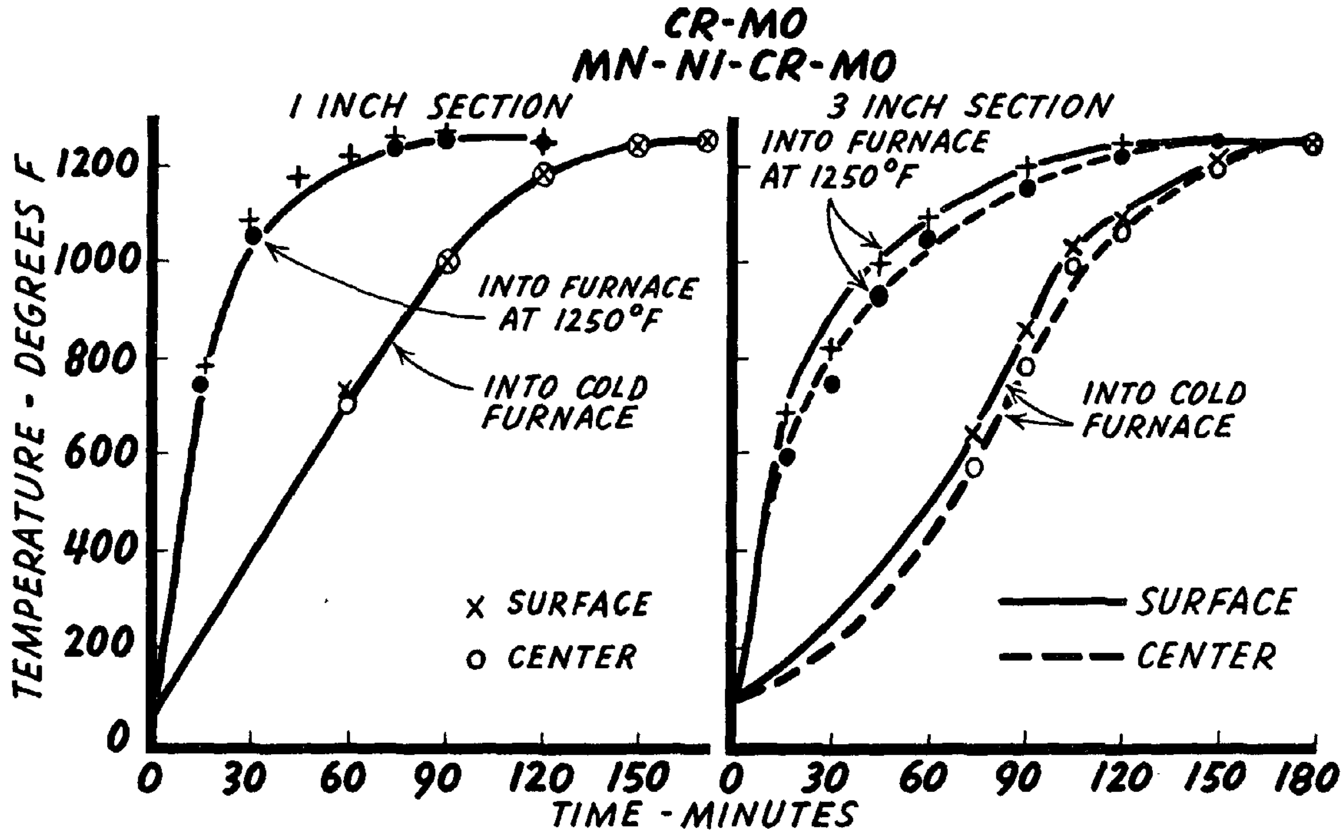


Figure 51—1- and 3-inch sections of Cr-Mo and Mn-Ni-Cr-Mo cast steels heated to 1250 degrees F in the production furnace at National Malleable and Steel Castings Co.

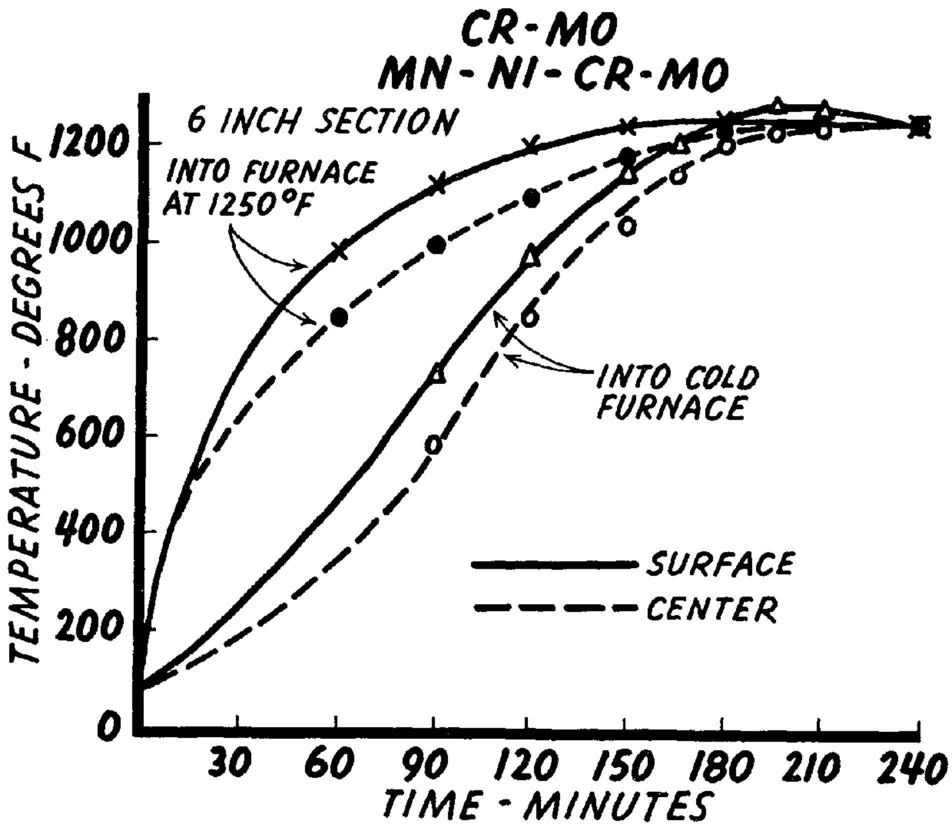


Figure 52—6-inch sections of Cr-Mo and Mn-Ni-Cr-Mo cast steel heated to 1250 degrees F in the production furnace at National Malleable and Steel Castings Co.

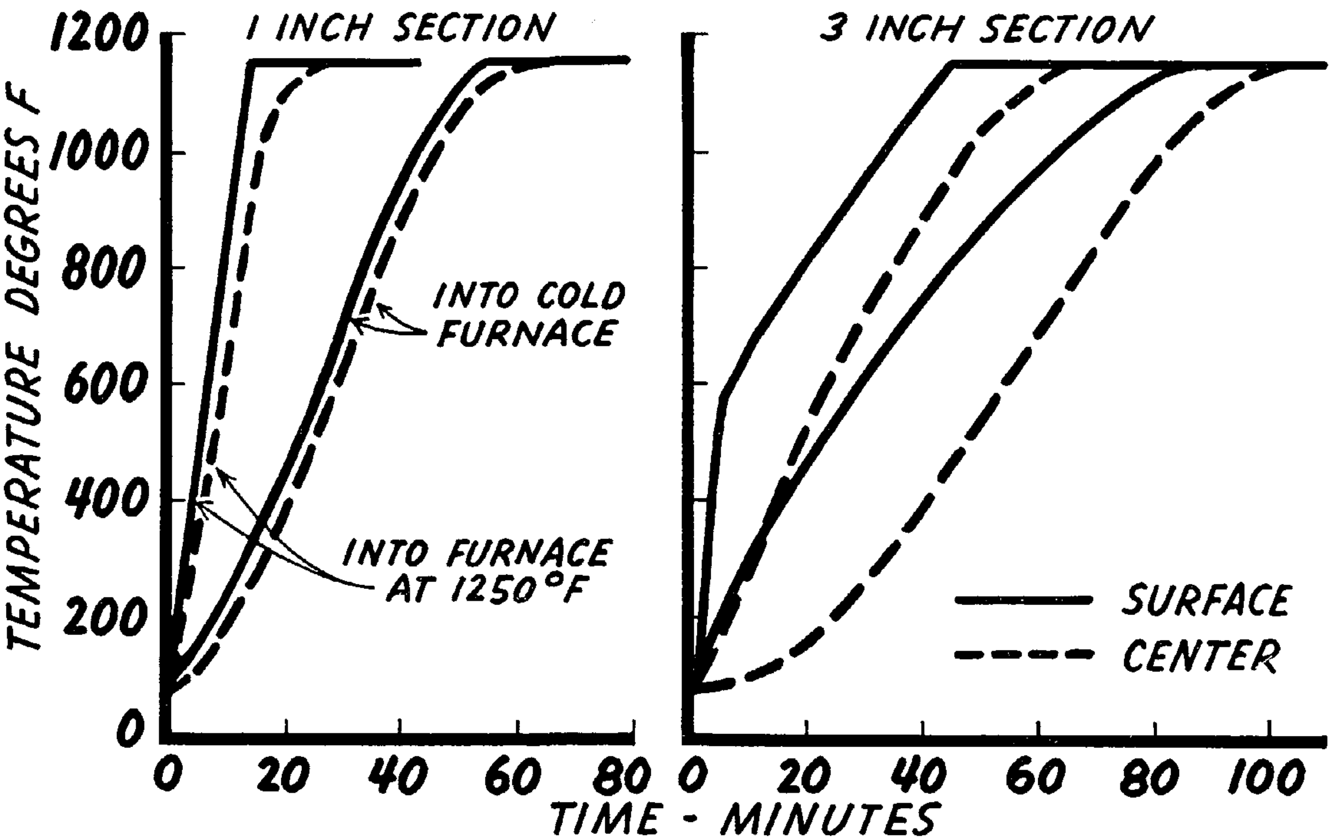


Figure 53—1- and 3-inch sections of Mn-B and Mn-Cr-Mo cast steels heated to 1250 degrees F in the experimental furnace at Pacific Car and Foundry Company.

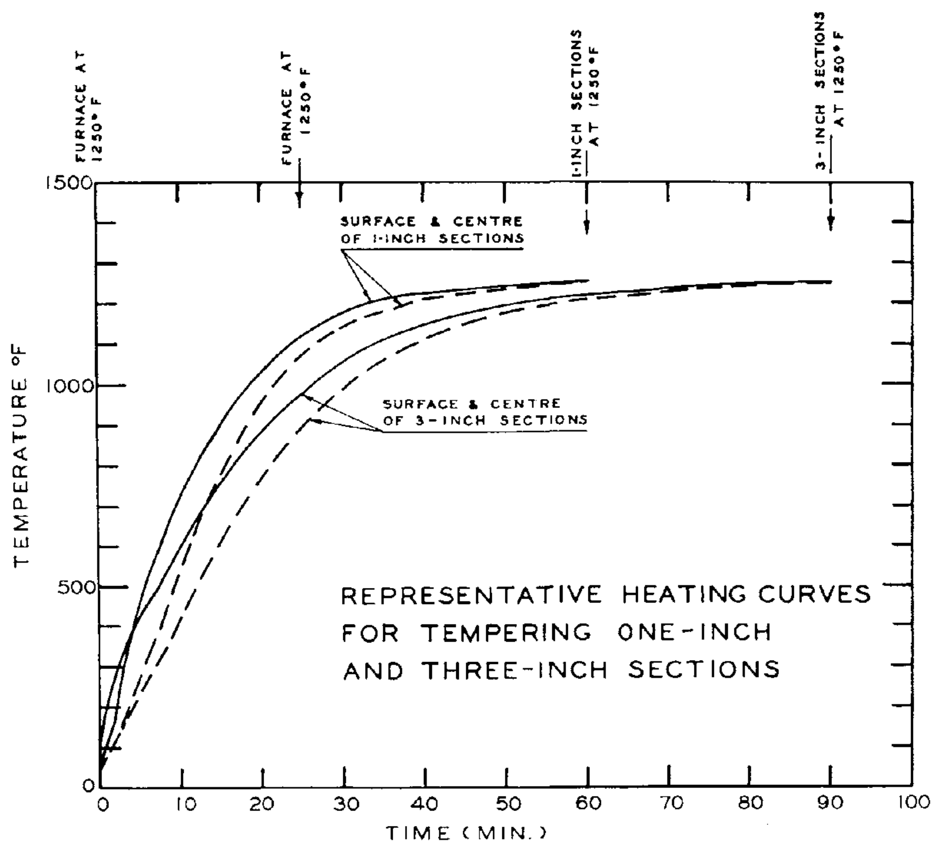


Figure 54—1- and 3-inch sections of carbon cast steel heated to 1250 degrees F in the experimental furnace of the Steel Castings Institute of Canada.

A comparison of the data for the homogenized and nonhomogenized steel prior to quenching shows that the hardness values, tensile strengths and yield points are slightly lower for the homogenized steels for any particular tempering temperature and time. If the same value is to be obtained then the unhomogenized steels must be tempered at a higher temperature or for a longer time; for example:

	T. S. 1000 psi	Temp. °F	Time, min.
A. Homogenized	93.5	1150	15
No Homogenize	93.4	1250	15
B. Homogenized	90.4	1250	15
No Homogenize	90.5	1250	30

The reason for this condition must be in carbon migration since all hardness readings were taken at the same depth level below the surface.

It has been observed in these studies, and by other casting producers, that the homogenization treatment results in decarburization so that it is necessary to grind to a depth of ⅛ to ¼ inch to obtain true hardness readings. Of course, this is another reason for the elimination of the homogenization heat treatment so as to maintain surface mechanical properties.

A comparison of the impact values shows no significant improvement with homogenization. In fact, both sets of values are much the same.

TABLE 29

Carbon Cast Steel; 1-inch Section
The Effect of Tempering Temperature and Time on Toughness and Tensile Properties

HEAT TEATMENT: Homogenize—(1) none; (2) 1650°F 2 hrs, air cool
Harden—1600°F 1 hour, water quench
Temper—950, 1050, 1150 and 1250°F for 15, 30, 90 and 300 minutes, air cool

Tempering		Not Homogenized			Homogenized		
			Charpy ft-lbs			Charpy ft-lbs	
Temperature °F	Time min.	BHN	+70°F	−40°F	BHN	+70°F	−40°F
950	15	247	32	16	234	41	16
	30	239	35	20	234	41	16
	90	235	37	19	228	38	20
	300	228	40	23	216	43	19
1050	15	235	36	22	222	42	22
	30	228	40	23	216	48	26
	90	225	47	25	205	50	23
	300	222	46	28	200	54	24
1150	15	205	50	22	216	48	25
	30	200	50	29	195	49	23
	90	195	50	26	190	54	24
	300	190	56	23	180	56	24
1250	15	200	54	29	190	58	27
	30	190	58	23	185	61	29
	90	185	61	27	180	60	25
	300	176	73	25	169	63	24

		Tempering Time-Minutes							
		Not Homogenized				Homogenized			
Property	Tempering Temp. °F	15	30	90	300	15	30	90	300
Tensile Strength 1000 psi	950	117.6	109.7	105.5	105.6	105.8	103.0	100.7	97.8
	1050	105.2	101.8	100.1	96.3	99.4	97.8	95.8	94.1
	1150	96.0	93.5	92.1	89.3	93.5	91.1	89.8	87.1
	1250	93.4	90.5	88.1	83.9	90.4	87.6	85.5	82.3
Brinell No.	950	247	239	235	228	234	234	228	216
	1050	235	228	228	222	222	216	205	200
	1150	205	200	195	195	216	195	190	180
	1250	200	190	185	176	190	185	180	169
Yield Point 1000 psi	950	—	79.2	78.6	80.2	82.2	79.3	76.6	74.6
	1050	77.4	74.4	74.2	70.6	76.2	72.6	71.6	70.7
	1150	69.4	66.7	66.8	63.9	68.9	67.3	66.9	63.3
	1250	68.7	64.9	65.5	61.1	66.1	63.9	64.1	59.1
Elon. %	950	15.8	18.6	19.6	23.6	17.8	20.1	22.8	23.3
	1050	18.8	21.1	21.0	23.1	20.5	22.8	24.8	29.1
	1150	23.0	25.3	26.6	28.1	24.8	28.6	28.6	29.1
	1250	24.1	26.8	28.0	29.3	27.6	27.0	30.6	30.6
Red. of Area %	950	35.6	43.4	47.0	48.1	36.9	45.4	50.5	49.7
	1050	36.1	45.1	47.7	51.7	42.4	48.4	50.4	54.4
	1150	46.6	52.7	55.2	57.3	51.6	56.5	57.5	59.6
	1250	50.8	58.0	60.2	60.0	53.9	57.4	62.6	61.6

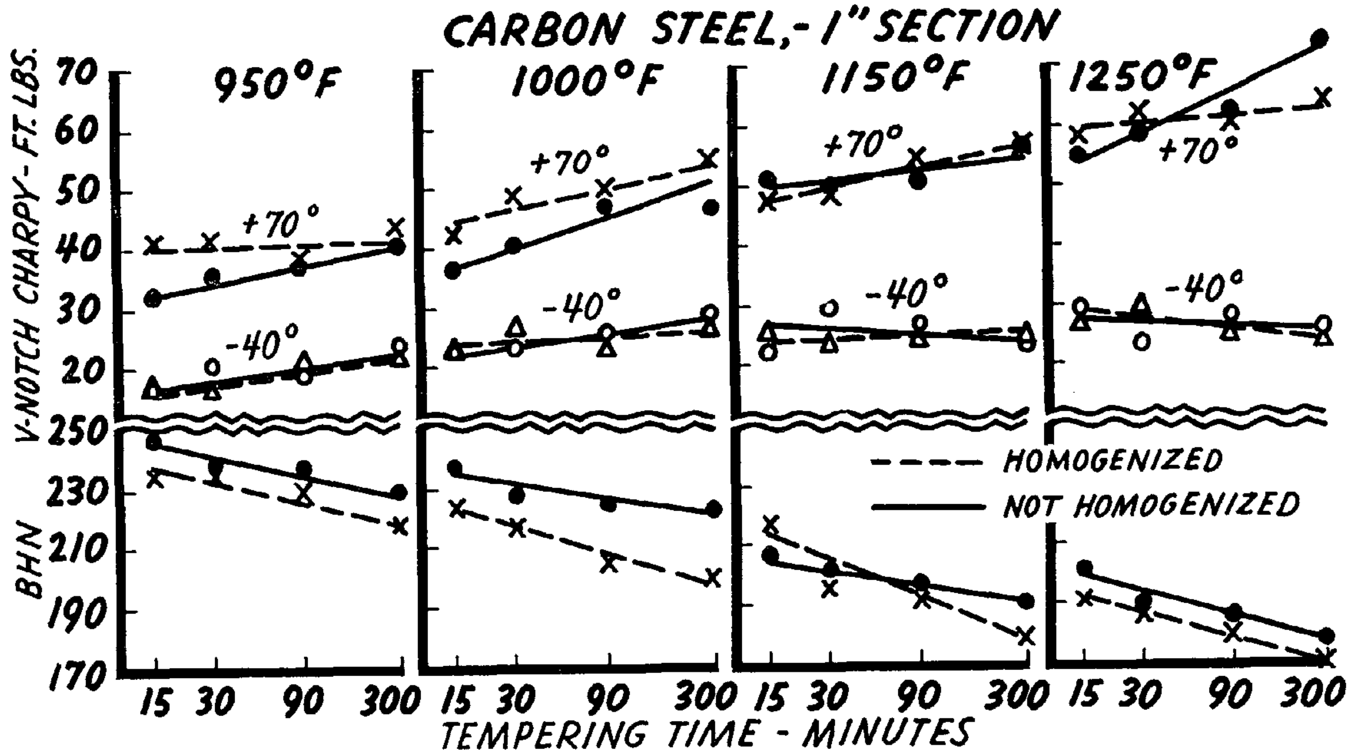


Figure 55– The effect of tempering on the Charpy V-notch impact properties of water quenched carbon cast steel. Heat treatment prior to quenching: (1) none; (2) homogenization at 1650 degrees F for 2 hours, air cooled.

If the reader observes only the impact values at any one temperature, he would immediately come to the conclusion that the impact properties improve as the tempering time increases. However, this is an erroneous assumption because the hardness values are decreasing at the same time and it is only proper that the impact values should increase. Figure 55 shows the impact-time-hardness values very well. This relationship should be kept in mind when analyzing these values.

There are not too many values in Table 29 that are directly comparable but, as an example, if 216 Brinell is selected as a constant, about the same impact value of approximately 48 foot/pounds can be obtained from the following combinations:

950°F-300 min; 1050°F-30 min; 1150°F-15 min.

Ductility as measured by reduction of area is favored by the use of the higher tempering temperature and increasing lengths of tempering times. Essentially this is only another way of saying that hardness is the controlling factor, and not how it is obtained. The microstructures of the carbon steel homogenized prior to water quenching are shown at various tempering temperatures and times in Figure 56, and the series which did not have the prior homogenizing treatment is illustrated in Figure 57. Little difference can be distinguished between the microstructures. Perhaps it can be said that the prior homogenizing (normalizing) treatment refined the grain size somewhat but, if so, it had no effect on the rate of tempering or the mechanical properties.

Tempering Mn-B Cast Steels

The tempering studies of the Mn-B cast steels were primarily carried out on 1-inch section coupons but some supplementary studies were made on 3-inch section coupons. Also, a homogenization treatment was performed prior to the water quench and the results were compared with similar studies made on steels without the prior homogenization treatment. The homogenization treatment prior to the quench was for 300 minutes at 1650 degrees F. Impact and tensile test results for the 1-inch and 3-inch sections may be compared in Table 30.

The impact properties for the Mn-B cast steel are low, especially the values at –40 degrees F and they do not improve much with the use of the high tempering temperatures as indicated by Figure 58. Also, this graph points out that the employment of a homogenization treatment prior to the quench did not improve the impact or tensile properties. Also, a short time at temperature produces as good values as the long time tempering treatment.

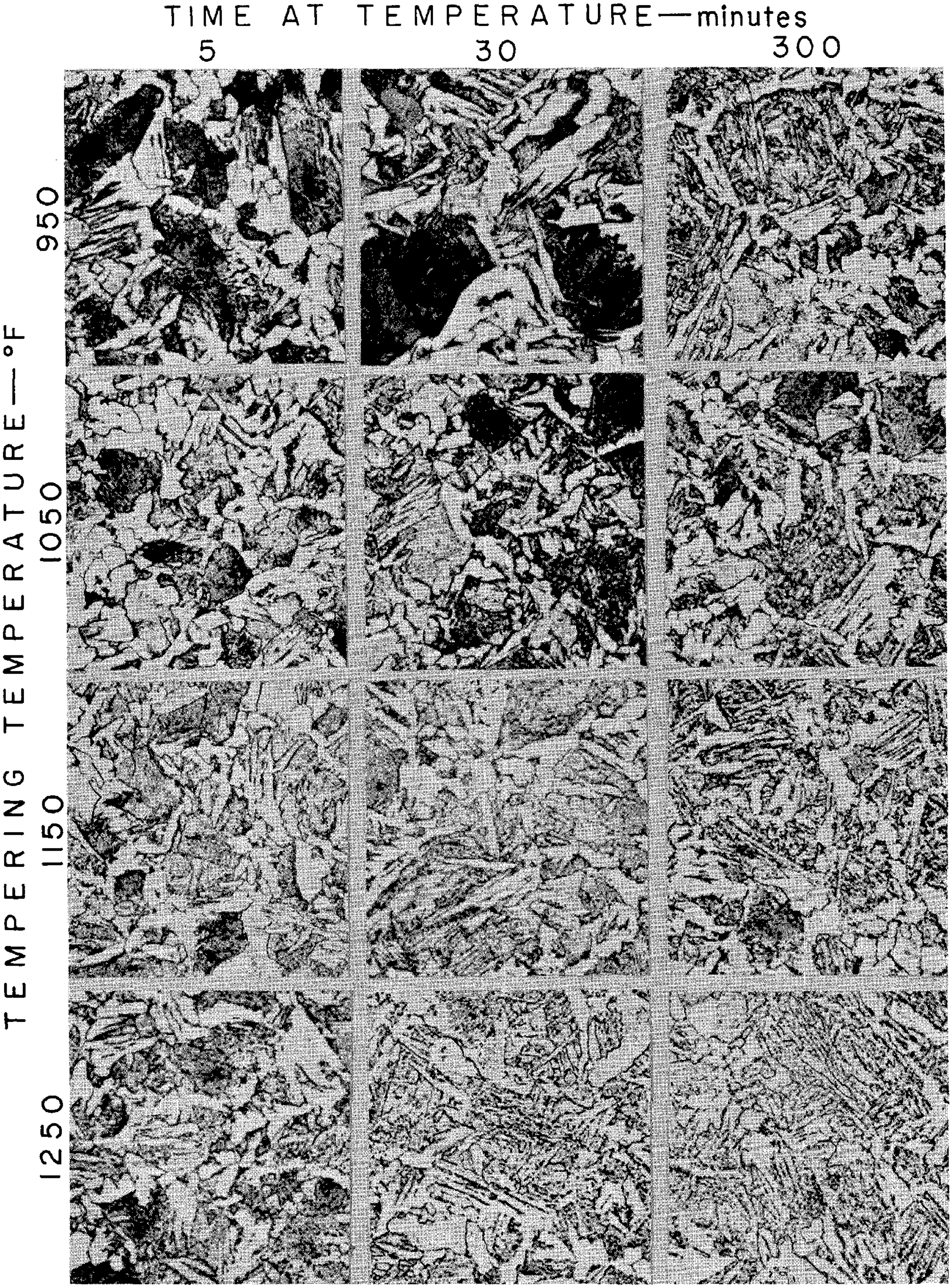


Figure 56—Center of 1-inch, 0.30 percent carbon steel section tempered at various times and temperatures following a homogenization heat treatment of 1650 degrees F for 2 hours, air cooled, heated to 1600 degrees F for 1 hour, water quenched. Etched in Nital. 1000X reduced ⅓ in reproduction.

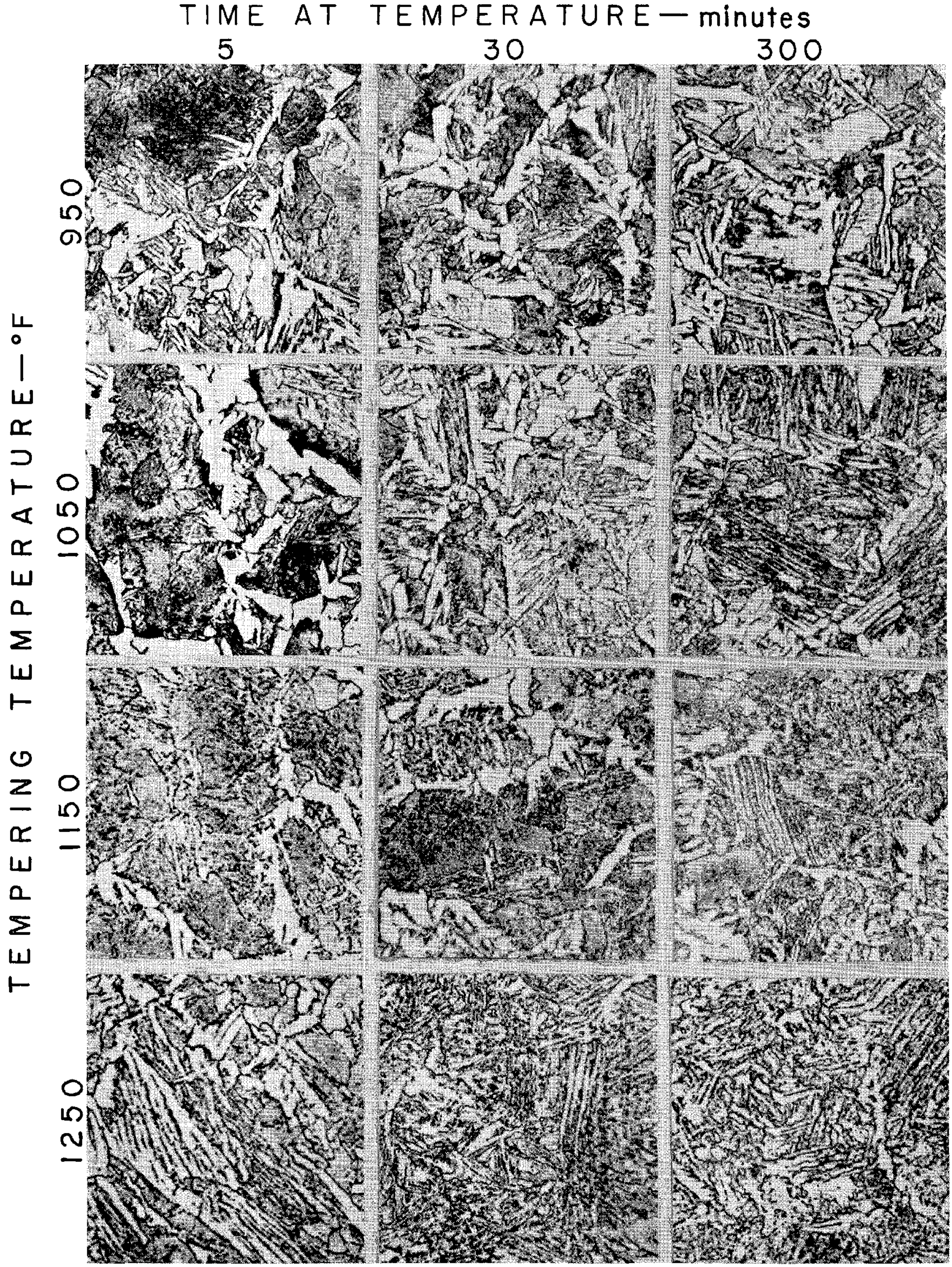


Figure 57—Tempered carbon cast steel. Same as Figure 56, except that no heat treatment prior to the quenching treatment was given. 1000X reduced ⅓ in reproduction. Nital etch.

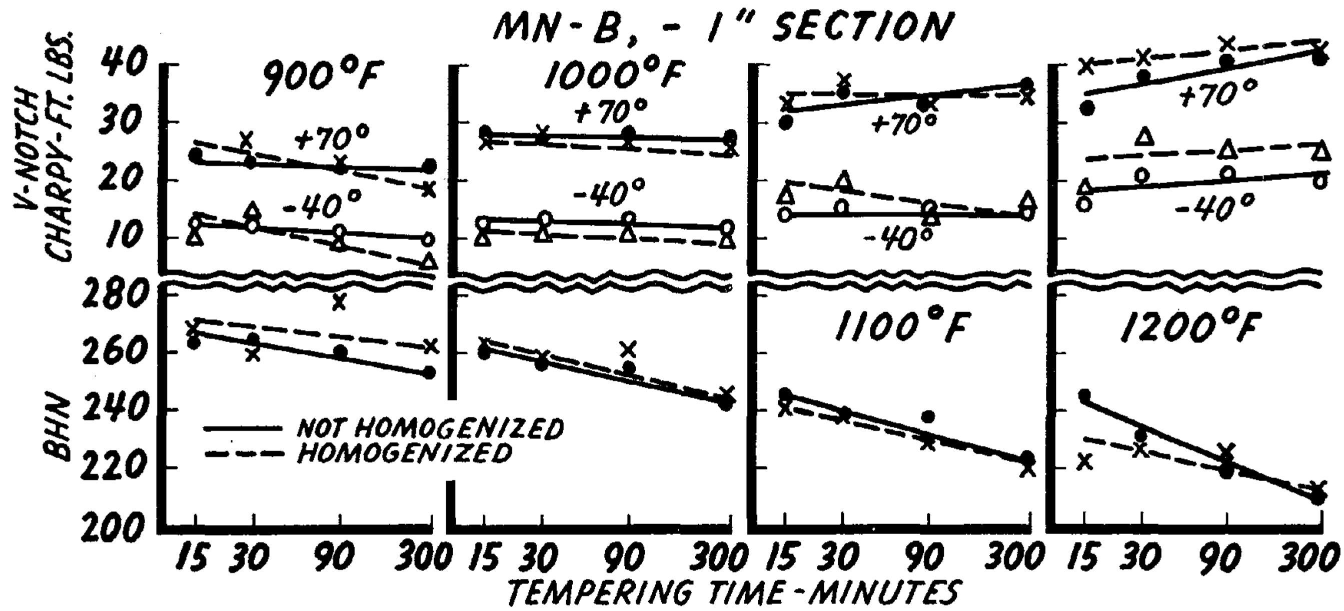


Figure 58—The effect of temperature and time on the tempering of water quenched Mn-B cast steel - 1-inch section. Heat treatment prior to quenching: (1) none; (2) homogenization at 1650 degrees F for 300 minutes. Air cooled.

TABLE 30

Mn-B Cast Steel; 1- and 3-inch Sections
The Effect of Tempering Temperature and Time on Toughness and Tensile Properties

HEAT TREATMENT: Homogenize—(1) none; (2) 1650°F for 300 min., air cool
Harden—1550°F for 90 min., water quench
Temper—900, 1000, 1100, 1200°F for 15, 30, 90, 300 minutes, water quench

Tempering Tempera-ture °F	Time min.	1-inch Not Homogenized BHN	Charpy V-Notch Impact ft-lbs +70°F	-40°F	1-inch Homogenized BHN	+70°F	-40°F	3-inch Homogenized BHN	+70°F	-40°F
900	15	264	24	11	272	23	11			
	30	267	23	11	257	27	13			
	90	262	22	9	280	23	9			
	300	253	22	8	264	18	5			
1000	15	264	28	13	267	26	12			
	30	257	27	13	255	28	12			
	90	257	28	13	260	27	11			
	300	241	27	10	244	25	9			
1100	15	246	30	14	241	33	17			
	30	237	36	15	237	37	19			
	90	235	34	14	227	34	14			
	300	221	36	14	221	36	16			
1200	15	243	32	16	221	39	17	204	38	11
	30	229	38	20	225	41	27	203	40	17
	90	219	41	21	225	43	25	192	50	15
	300	210	41	20	205	42	24	—	—	—

Temp. °F	Time min.	Prior Homo. Treat.	T. S. 1000 psi	Yield 1000 psi	Elonga-tion %	Red. of Area %	BHN
900	30	No	130.8	118.0	11.0	24.4	272
	30	Yes	136.5	127.4	13.0	32.6	280
1000	15	No	129.5	115.0	14.5	32.7	264
	15	Yes	131.2	120.0	10.5	19.2	267
1100	15	No	119.0	104.2	13.0	22.7	246
	15	Yes	118.0	106.0	13.5	22.7	241
1200	30	No	112.2	96.2	16.5	34.3	229
	30	Yes	109.8	97.2	17.5	34.3	225
1200†	30	Yes	104.0	86.0	22.5	50.8	203

† 3-inch section

The microstructures of the Mn-B cast steel are illustrated in Figure 59. The prior homogenization treatment had a definite effect on the structure of the 1-inch section, even though there was no influence of it on the mechanical properties.

Tempered Mn-Cr-Mo Cast Steel

The Mn-Cr-Mo cast steel was studied primarily in the 1-inch section and was quenched from 1650 degrees F after a holding time of 90 minutes and tempered at 1050, 1075, 1150, 1175 and 1250 degrees F. One set of test coupons was given a homogenization treatment of 1750 degrees F for 300 minutes and the other set was not homogenized. A few studies were made on 3-inch section blocks for comparison purposes.

The impact and tensile properties of the 1-inch and 3-inch section coupons are summarized in Table 31.

The values of Table 31 are plotted in Figure 60. The specimens that received the prior homogenization heat treatment produced the higher impact properties. The difference is very noticeable for this steel. A comparison of the values at –40 degrees F is shown for two tempering temperatures on the chart of Figure 60.

The tensile ductility is low in several cases for this steel. This is most interesting in view of the fact that the low temperature impact values are very good. The ductility values for the 3-inch section were very poor.

The values of Table 31 are plotted in another manner in Figure 61 so that temperature can be selected for a definite impact value. It will be observed that at a constant hardness level of 300

TABLE 31

Mn-Cr-Mo Cast Steel; 1-inch Section
The Effect of Tempering Temperature and Time
on Toughness and Tensile Properties

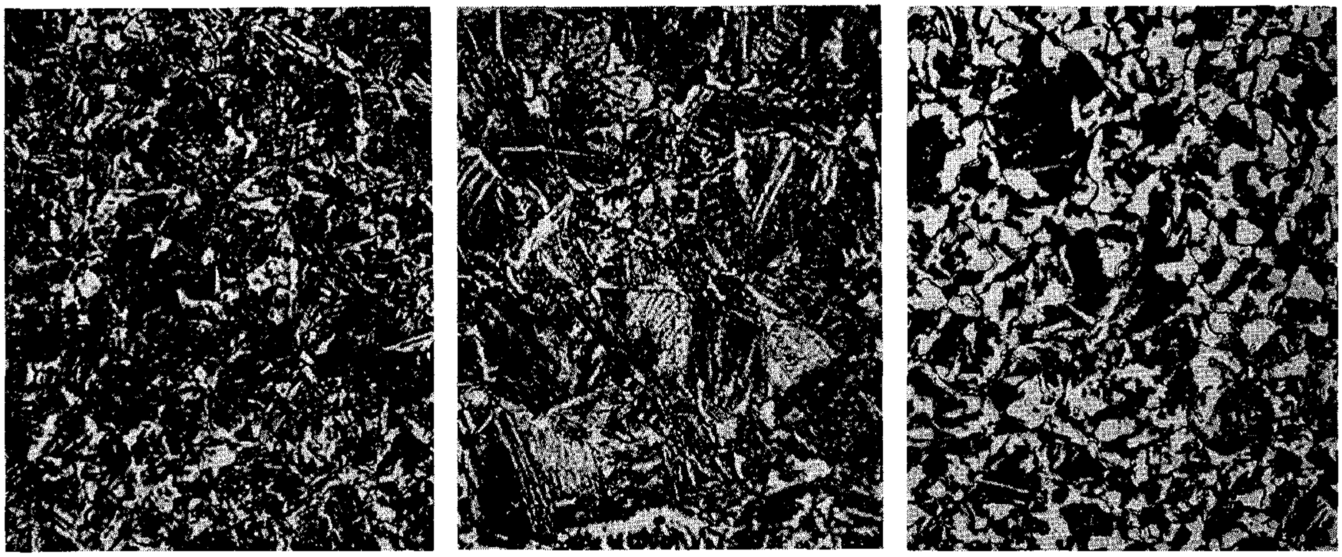
HEAT TREATMENT: Homogenize (1) none; (2) 1750°F for 300 min., air cool
Harden—1650°F, 90 min., water quench
Temper—1050, 1075, 1150, 1250°F for 15, 30, 90, 300 minutes, water quench

Tempering Temperature °F	Tempering Time min.	BHN	Not Homogenized +70°F	Not Homogenized –40°F	Not Homogenized –80°F	BHN	Homogenized +70°F	Homogenized –40°F	Homogenized –80°F
			Charpy V-Notch Impact, ft-lbs.						
1050	15	370	15	7	7	368	30	22	14
	30	370	22	10	8	359	30	24	14
	90	337	33	19	13	352	34	32	21
	300	306	41	26	19	321	41	39	33
1075	15	331	30	18	16	348	33	27	15
	30	343	31	—	15	343	30	24	20
	90	319	34	26	22	327	37	34	29
	300	300	44	37	35	302	47	38	36
1150	15	337	31	16	12	323	37	33	24
	30	345	33	21	25	307	40	41	41
	90	297	46	43	34	282	50	47	47
	300	272	53	46	35	263	57	48	50
1250	15	—	—	—	—	269	48	46	48
	30	—	—	—	—	274	51	51	48
	90	—	—	—	—	252	58	53	52
	300	—	—	—	—	229	58	55	55

Temp. °F	Time min.	Homo. Treat.	T. S. 1000 psi	Yield 1000 psi	Elongation %	Red. of Area %	BHN
1050	300	No	150.7	141.3	10.0	19.0	306
	300	Yes	153.6	142.5	10.0	15.7	321
1075	300	No	142.5	130.0	12.8	26.8	300
	90	Yes	158.5	148.7	12.0	28.7	327
1150	90	No	140.5	128.0	13.2	32.2	297
	30	Yes	146.8	138.0	11.7	19.5	307
1250	30	Yes	126.8	114.5	12.0	25.8	274

3-inch Section - Homogenized

°F	Min.	BHN	+70°F	–40°F	–80°F	T. S. 1000 psi	Y. P. 1000 psi	Elong. %	R. A. %
1150	15	282	45	22	15	—	—	—	—
	30	272	52	36	27	126.5	115.7	6.5	11.0
	90	271	52	27	21	—	—	—	—



a. 1-inch section. Homogenized 1650°F - 300 min., air cooled; 1550°F - 90 min., water quenched. Tempered 1200°F - 30 minutes

b. 1-inch section. No homogenization; 1550°F - 90 minutes, water quenched; tempered 1200°F - 30 minutes

c. 3-inch section. Homogenized 1650°F - 300 min., air cooled; 1550°F - 90 minutes, water quenched; tempered 1200°F - 30 minutes

Figure 59—Mn-B Cast Steel. Nital etch. 500X

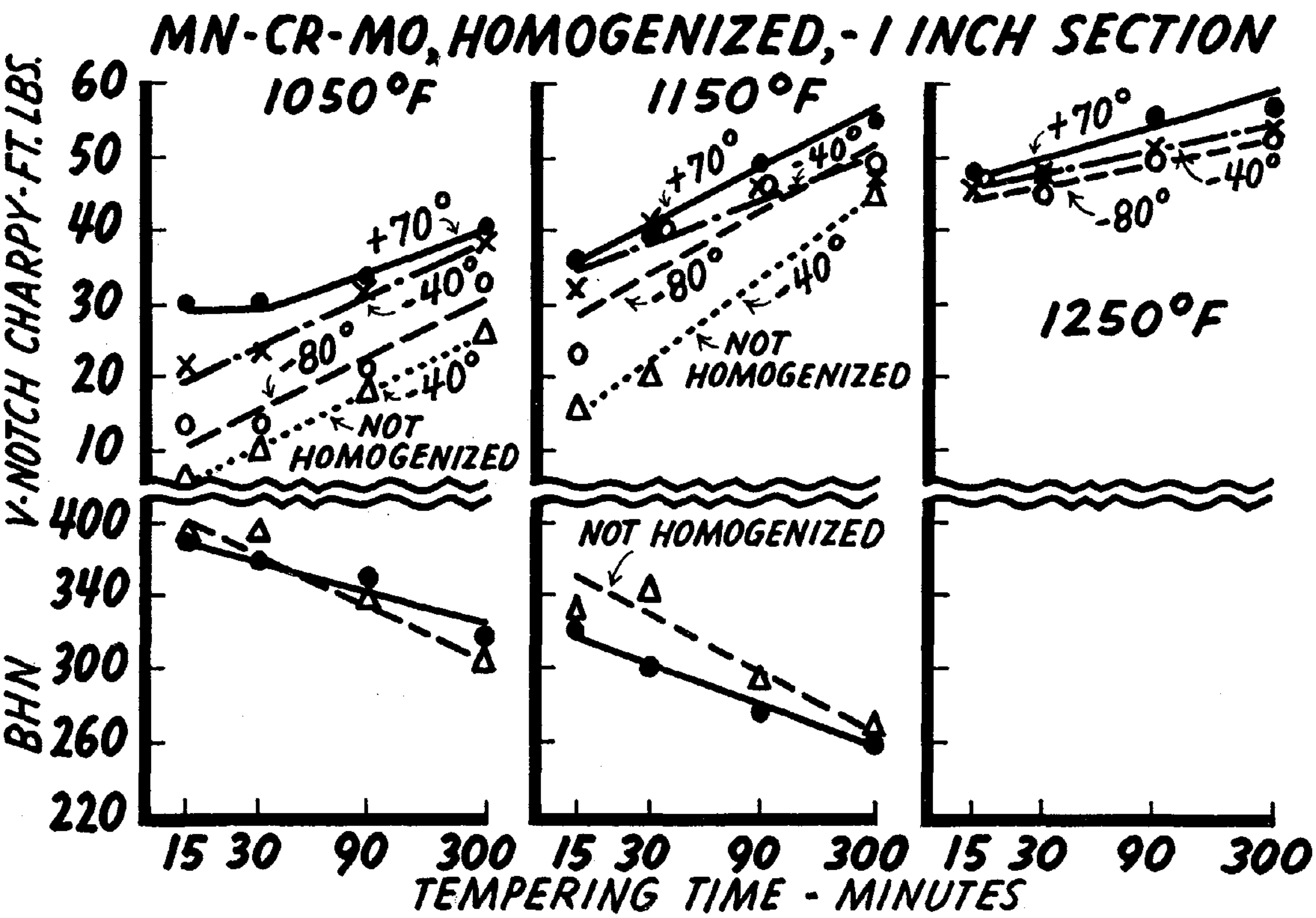


Figure 60—The effect of tempering on the Charpy V-notch impact properties of Mn-Cr-Mo cast steel - 1-inch section. Heat treatment prior to quenching: (1) none; (2) homogenization at 1750 degrees F for 300 minutes. Air cooled. Water quench from 1650 degrees F after 90 minutes. Water quenched from tempering temperature.

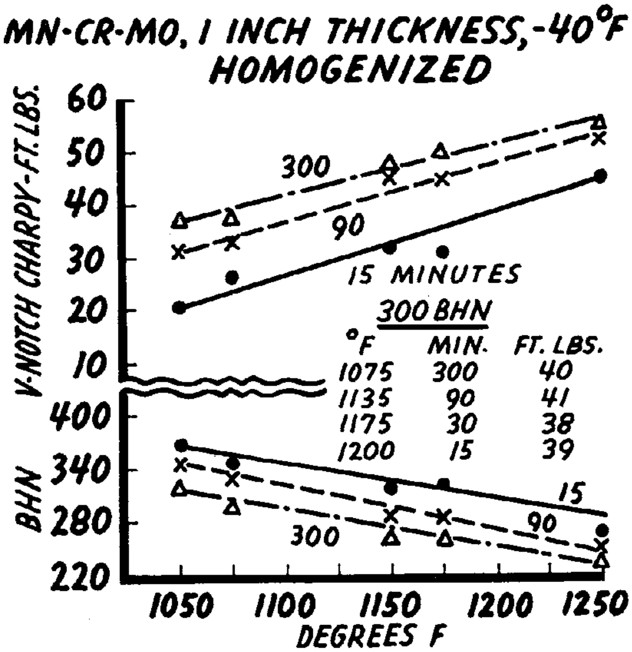


Figure 61—The importance of hardness in determining the time-temperature relationship in tempering Mn-Cr-Mo cast steel.

Brinell, the same impact values can be obtained whether a high tempering temperature-short heating time is employed or a long heating time at a low temperature.

The microstructures in Figure 62 are typical of all the structures obtained on tempering regardless of the tempering temperatures or time. A long time was selected to indicate the differences between the group with and without the prior homogenization heat treatment. Traces of the dendritic structure are still evident in the microstructure from the steel without the prior homogenization treatment.

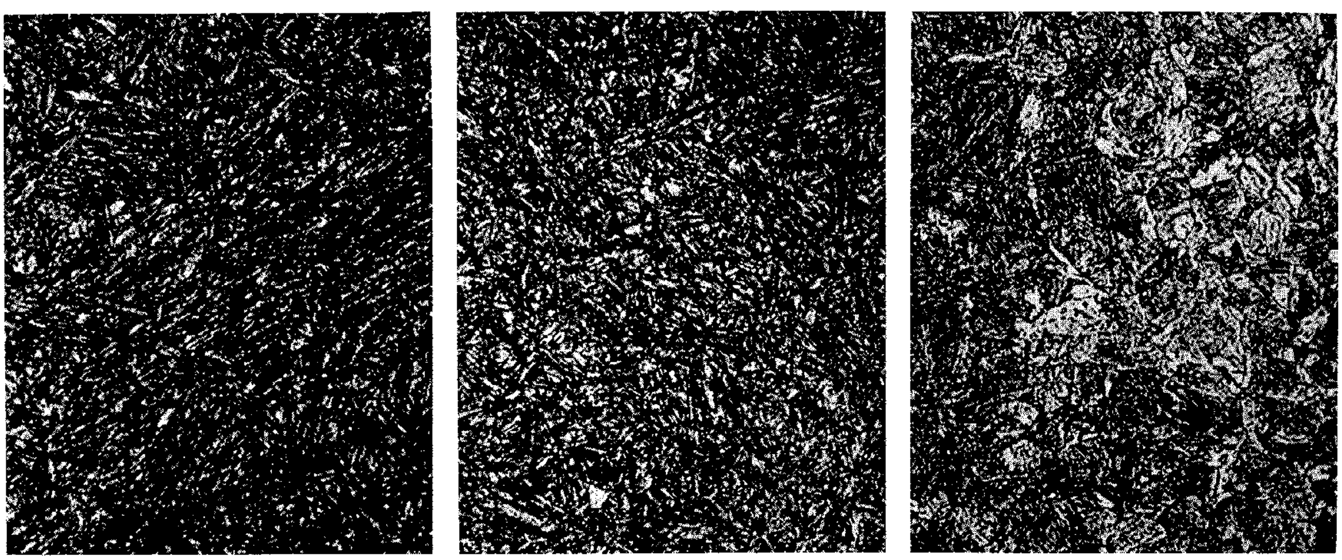
The three-inch section shows the presence of free ferrite at grain boundaries. It is for this reason that the properties of the 3-inch section are low. Apparently the composition is not adequate to permit the quenching out of a 3-inch section of the low-alloy content of this type of Mn-Cr-Mo cast steel.

Tempering Cr-Mo Cast Steel

Tempering studies for the Cr-Mo cast steel were carried on in three section sizes: 1-, 3- and 6-inch. Studies were made at three tempering temperatures for four different times. Impact and tensile properties were obtained on two groups of heat treatments: (1) a homogenization treatment of 1750 degrees F for 320 minutes prior to the quenching heat treatment, and (2) no prior homogenizing treatment. Again, no effort was made to hold the Brinell hardness values constant.

A summary of the impact and tensile values for the 1-, 3- and 6-inch sections are given in Tables 32, 33 and 34.

A review of these tables will indicate that the tensile strength values for all section sizes are primarily a function of the hardness, and the tempering times are of little or no importance. The data, however, are somewhat conflicting as to the importance of the effect of a prior homogenization heat treatment. The 3-inch section studies indicate that the homogenization treatment improved the ductility



a. 1-inch section. No homogenization; 1650°F - 90 minutes, water quenched; tempered 1050°F - 300 min.

b. 1-inch section. Homogenized 1750°F - 300 minutes, air cooled; 1650°F - 90 minutes, water quenched; tempered 1050°F - 300 min.

c. 3-inch section. Homogenized 1750°F - 300 minutes, air cooled; 1650°F - 90 minutes, water quenched; tempered 1150°F - 30 min.

Figure 62—Mn-Cr-Mo Cast Steel. Nital etch. 500X

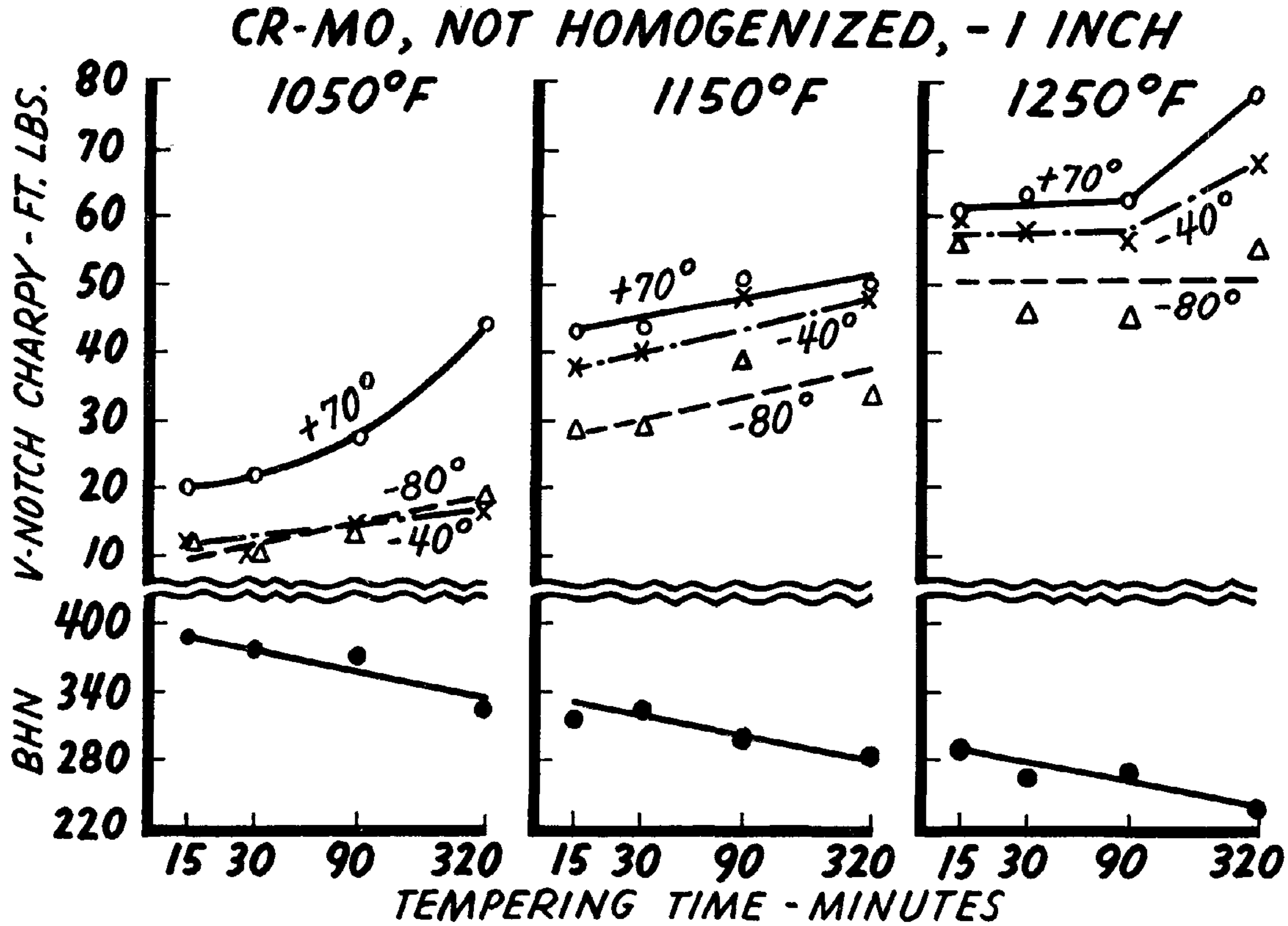


Figure 63—The effect of tempering time and temperature on the Charpy V-notch impact properties of unhomogenized Cr-Mo cast steel - 1-inch section. Heat treatment prior to quenching: none. Heated to 1650 degrees F for 90 minutes, water quenched and tempered. Water quenched from tempering temperature.

properties considerably. However, a review of the 6-inch section data shows that the best ductility values were secured by the steel which did not receive a prior homogenization treatment. The 1-inch section studies showed no definite trends one way or the other.

The impact values were plotted for purposes of comparison. Figures 63 and 64 show the trends for the 1-inch section. Perhaps the first thing that should be pointed out is that as the tempering time increases, at any one tempering temperature, the hardness of the steel decreases. The impact properties naturally increase as the hardness decreases.

The homogenized 1-inch thick Cr-Mo steel has the better impact properties at the lower tempering temperatures. But at 1250 degrees F tempering temperature there is no advantage in employing a prior homogenizing heat treatment.

The 3-inch sections (Figures 65, 66) do not show the pronounced differences between unhomogenized and homogenized impact values at the different tempering temperatures. The results for the 6-inch sections (Figures 67, 68) indicate that the impact values are similar, irrespective of whether they received or did not receive a prior homogenization treatment.

The effect of section size on the impact properties at –40 degrees F of the unhomogenized Cr-Mo cast steel is illustrated in Figure 69. The impact properties correlate very well with the Brinell hardness and there is not too much difference in the curves on the basis of section thickness. A single curve could just as well be drawn through all of the points instead of drawing three separate curves.

Again, a comparison is made (Figure 70) for the 1-inch section at –40 degrees of the impact values for both the homogenized and unhomogenized heat treatments since at this section thickness the use of a prior heat treatment produced the widest divergence in impact values. It seems evident that at the

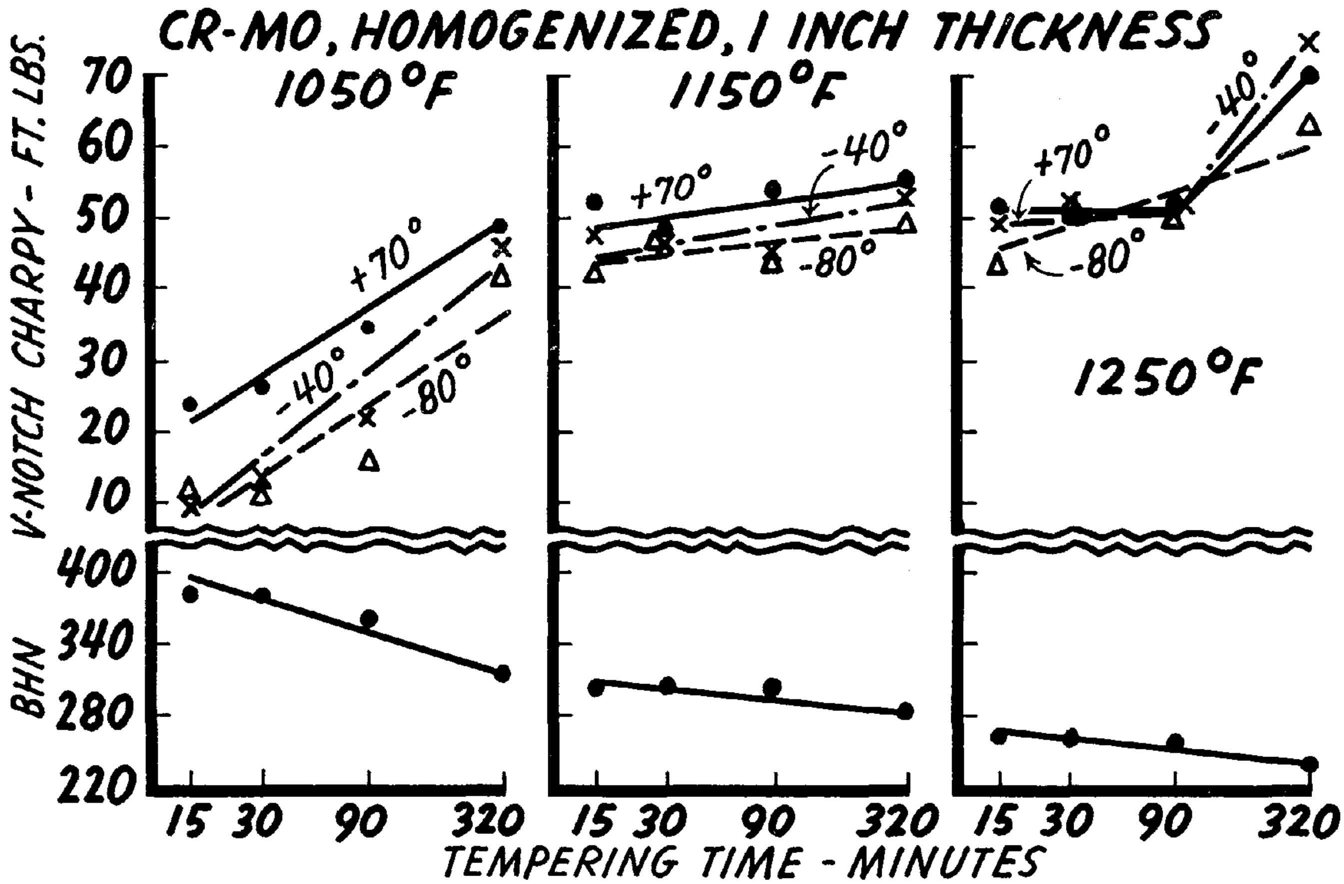


Figure 64—The effect of tempering time and temperature on the Charpy V-notch impact properties of homogenized Cr-Mo cast steel - 1-inch section. Heat treatment: homogenized 1750 degrees F for 320 minutes, air cooled. Harden: 1650 degrees F for 90 minutes, water quenched and tempered. Water quenched from tempering temperature.

TABLE 32
Cr-Mo Cast Steel - 1-inch Section
The Effect of Tempering Temperature and Time on Toughness and Tensile Properties

HEAT TREATMENT: Homogenize—(1) none; (2) 1750°F for 320 min., air cool
Harden—1650°F, 90 min., water quench
Temper—1050, 1150, 1250°F for 15, 30, 90 320 min., water quench

Tempering			Charpy V-Notch Impact, ft-lbs.						
			Not Homogenized				Homogenized		
Temperature °F	Time min.	BHN	+70°F	–40°F	–80°F	BHN	+70°F	–40°F	–80°F
1050	15	388	20	11	11	383	23	10	11
	30	376	22	10	10	383	26	13	11
	90	370	27	14	13	357	35	22	15
	320	320	44	26	18	311	49	46	44
1150	15	317	43	38	28	301	52	48	43
	30	320	44	40	28	300	48	47	47
	90	299	52	48	39	297	53	45	45
	320	281	50	48	33	282	56	54	50
1250	15	286	61	60	56	264	51	49	43
	30	260	63	58	45	257	50	52	51
	90	264	62	56	44	254	52	52	49
	320	230	78	68	55	230	70	75	62

Temp. °F	Time min.	Homo. Treat.	T. S. 1000 psi	Yield 1000 psi	Elonga-tion %	Red. of Area %	BHN
1050	320	No	151.6	126.8	11.0	38.0	321
	320	Yes	150.8	125.8	12.8	44.9	316
1150	320	No	139.2	113.3	14.7	47.5	302
	90	Yes	136.7	110.0	13.3	42.7	297
1250	30	No	131.1	104.6	13.2	38.6	278
	30	Yes	130.7	105.2	14.0	39.1	269

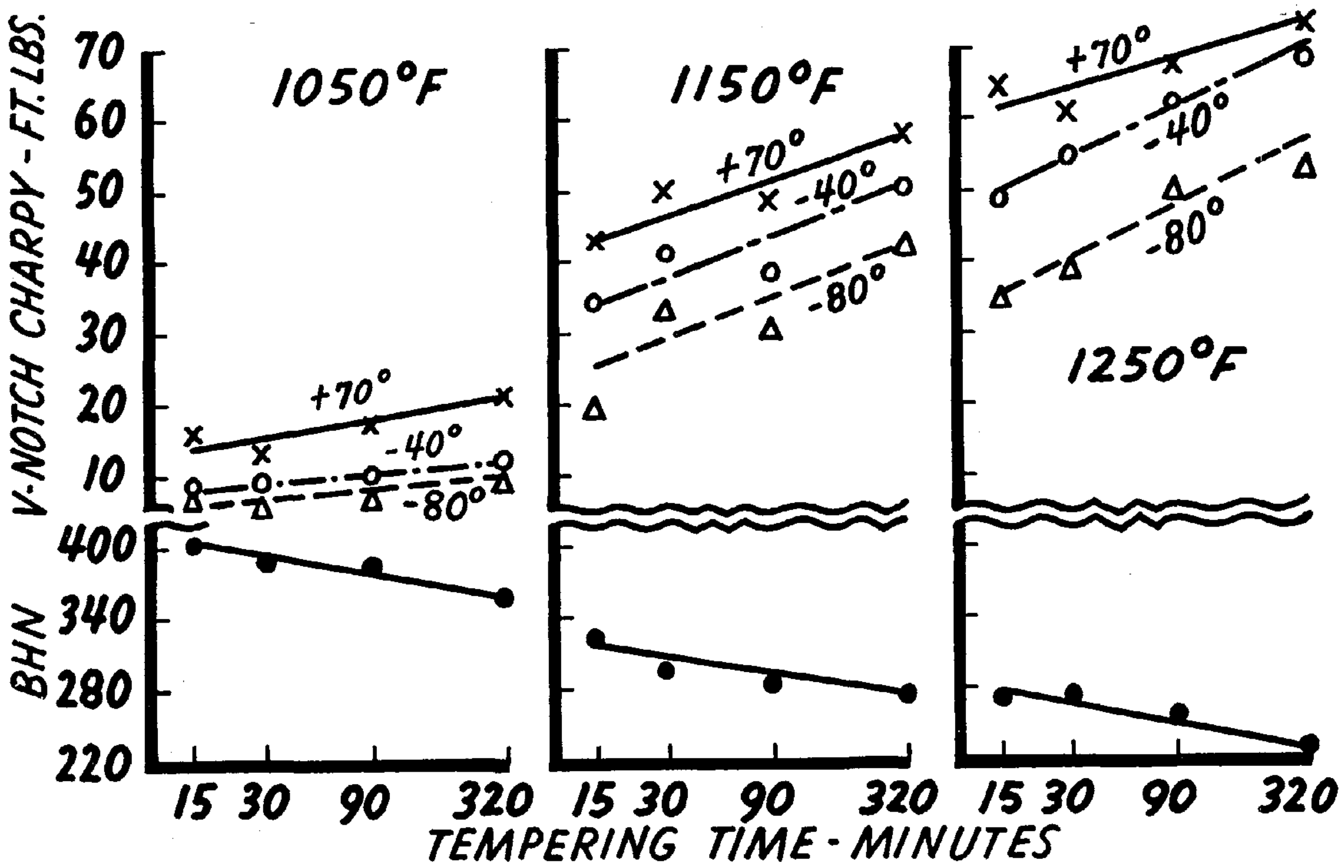


Figure 65—The effect of tempering time and temperature on the Charpy V-notch impact properties of unhomogenized Cr-Mo cast steel - 3-inch section. Heat treatment prior to quenching: none. Heated to 1650 degrees F for 90 minutes, water quenched and tempered. Water quenched from tempering temperature.

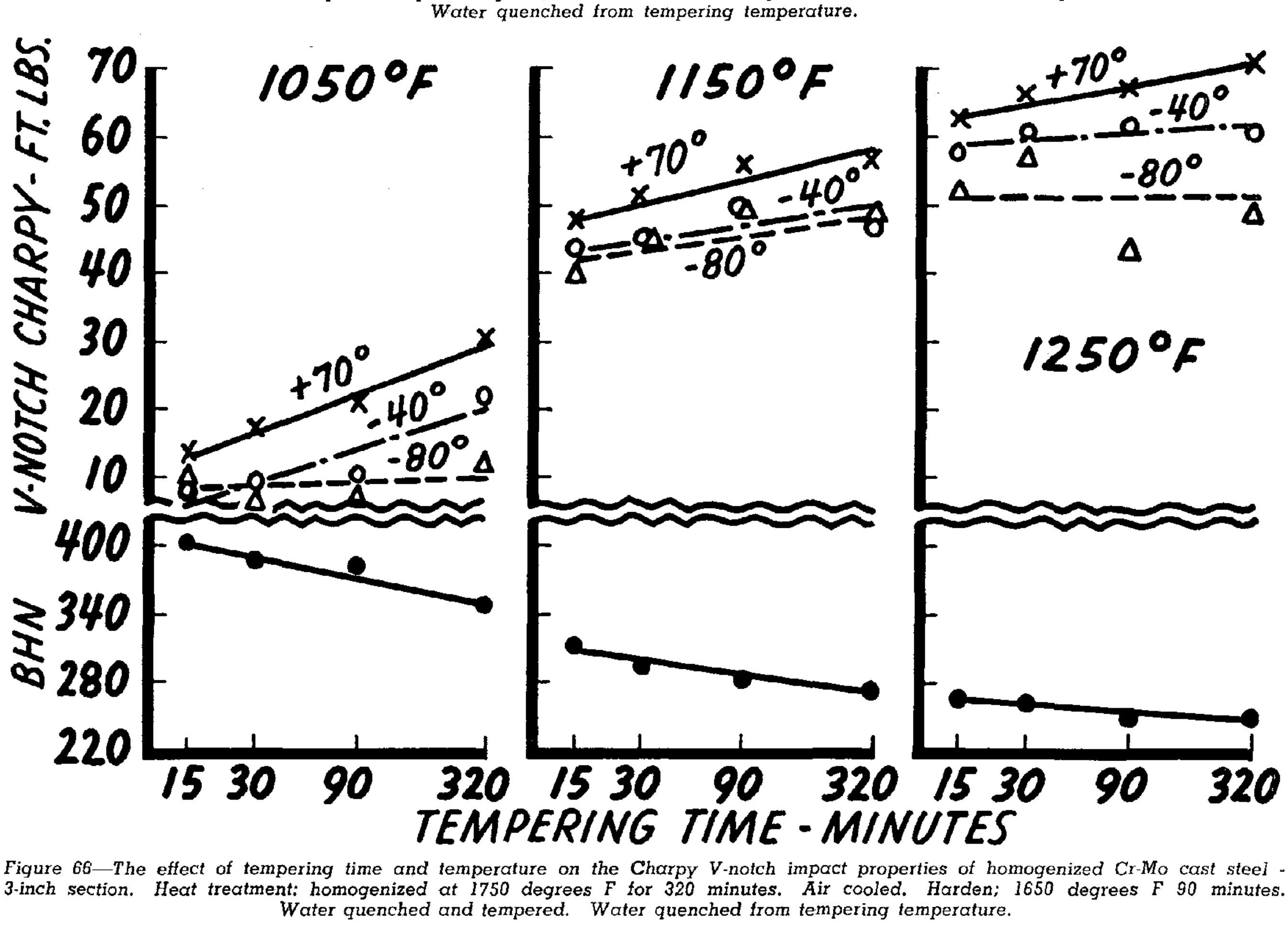


Figure 66—The effect of tempering time and temperature on the Charpy V-notch impact properties of homogenized Cr-Mo cast steel - 3-inch section. Heat treatment: homogenized at 1750 degrees F for 320 minutes. Air cooled. Harden; 1650 degrees F 90 minutes. Water quenched and tempered. Water quenched from tempering temperature.

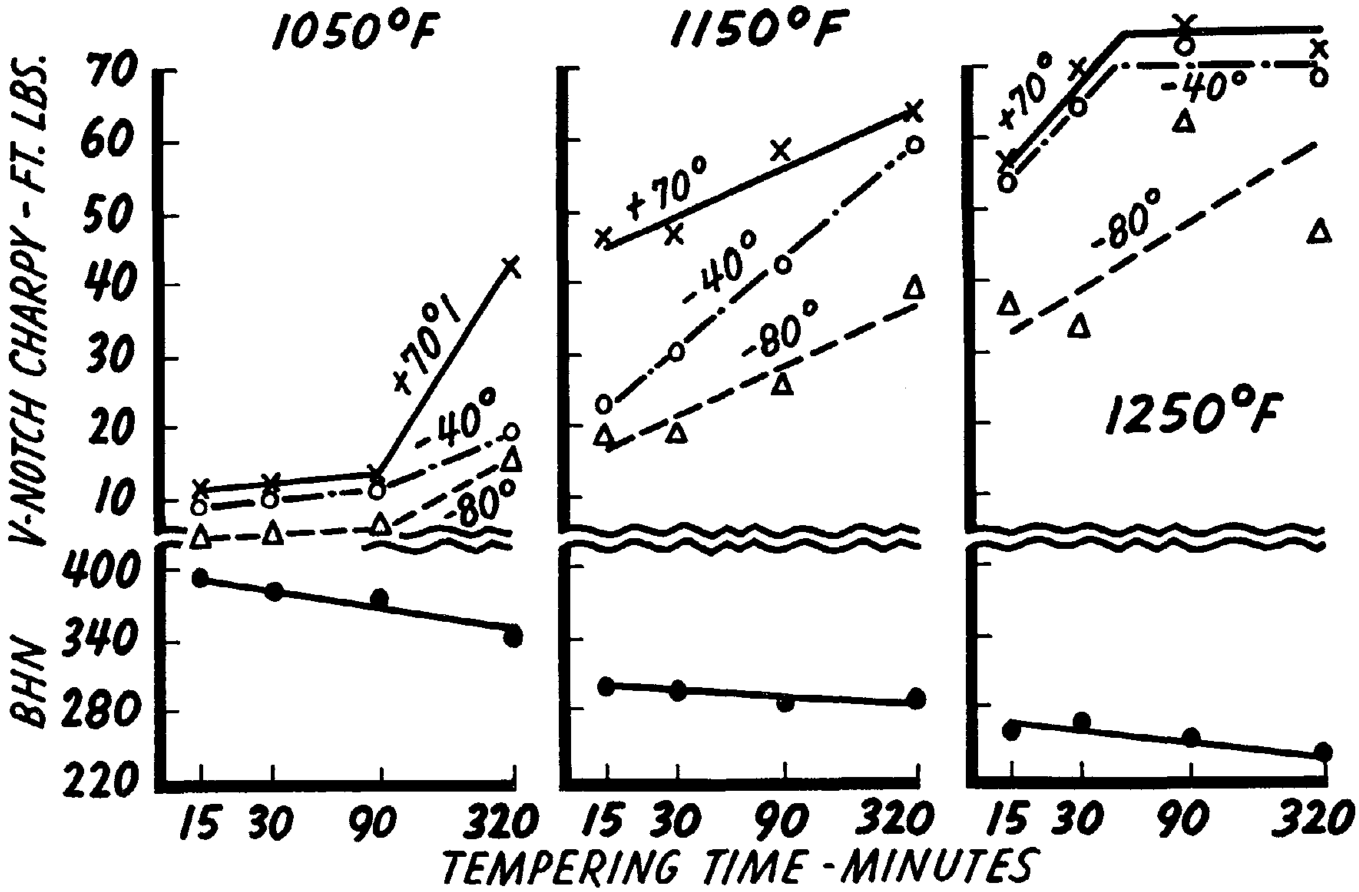


Figure 67—The effect of tempering time and temperature on the Charpy V-notch impact properties of unhomogenized Cr-Mo cast steel - 6-inch section. Heat treatment prior to quenching: none. Heated to 1650 degrees F for 90 minutes, water quenched and tempered. Water quenched from tempering temperature.

TABLE 33

Cr-Mo Cast Steel - 3-inch Section

The Effect of Tempering Temperature and Time on Toughness and Tensile Properties

HEAT TREATMENT: Homogenize—(1) none; (2) 1750°F for 320 min., air cool
Harden—1650°F, 90 min., water quench
Temper—1050, 1150, 1250°F for 15, 30, 90, 320 min., water quench

Tempering			Charpy V-Notch Impact, ft-lbs.						
			Not Homogenized				Homogenized		
Temperature °F	Time min.	BHN	+70°F	−40°F	−80°F	BHN	+70°F	−40°F	−80°F
1050	15	400	15	8	6	400	13	8	9
	30	390	13	8	5	386	17	9	7
	90	381	18	9	8	381	21	10	8
	320	353	31	11	11	344	30	22	11
1150	15	320	44	34	19	307	48	44	41
	30	294	49	46	33	296	51	45	45
	90	286	48	43	31	283	56	51	50
	320	271	58	52	42	275	57	47	48
1250	15	273	65	49	35	269	62	58	52
	30	258	62	55	39	259	66	61	57
	90	244	68	63	50	243	67	61	43
	320	225	75	69	54	232	70	60	49

Temp. °F	Time min.	BHN	Homo. Treat.	T. S. 1000 psi	Yield 1000 psi	Elongation %	Red. of Area %
1050	15	340	No	161.4	141.5	7.0	21.7
	90	316	Yes	150.0	126.8	10.3	32.6
1150	30	310	No	137.6	114.3	7.3	18.7
	90	300	Yes	134.7	111.0	12.0	37.4
1250	30	273	No	124.2	102.2	9.5	27.4
	30	269	Yes	123.3	102.6	14.0	40.5

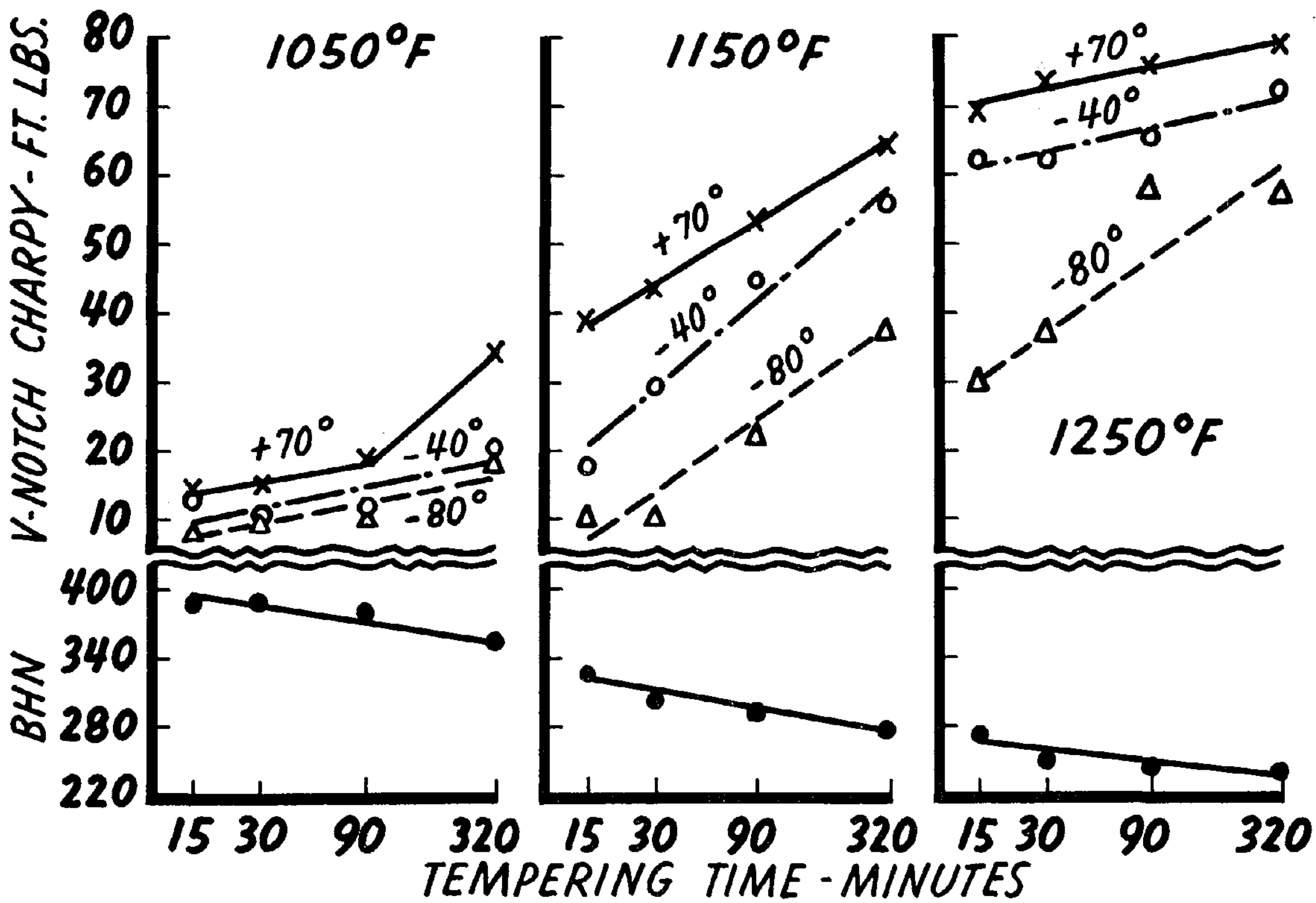


Figure 68—The effect of tempering time and temperature on Charpy V-notch impact properties of homogenized Cr-Mo cast steel - 6-inch section. Heat treatment: homogenized 1750 degrees F for 320 minutes. Air cooled. Harden; 1650 degrees F 90 minutes. Water quenched and tempered. Water quenched from tempering temperature.

TABLE 34

Cr-Mo Cast Steel - 6-inch Section

The Effect of Tempering Temperature and Time on Toughness and Tensile Properties

HEAT TREATMENT: Homogenize—(1) none; (2) 1750°F for 320 min, air cool
Harden—1650°F, 90 min., water quench
Temper—1050, 1150, 1250°F for 15, 30, 90, 320 min., water quench

Tempering			Charpy V-Notch Impact, ft-lbs.						
			Not Homogenized				Homogenized		
Temperature °F	Time min.	BHN	+70°F	−40°F	−80°F	BHN	+70°F	−40°F	−80°F
1050	15	392	11	9	4	390	14	14	8
	30	386	12	10	5	386	15	9	9
	90	377	13	11	7	371	19	11	10
	320	344	43	19	16	348	34	20	18
1150	15	300	46	23	19	321	39	18	10
	30	295	47	30	19	309	43	29	16
	90	287	58	42	25	291	53	44	22
	320	281	63	59	39	275	64	56	37
1250	15	264	57	54	36	268	69	62	30
	30	264	70	65	33	250	73	62	37
	90	253	76	73	62	246	76	65	58
	320	240	73	69	46	237	79	72	56

Temp. °F	Time min.	BHN	Homo. Treat.	T. S. 1000 psi	Yield 1000 psi	Elongation %	Red. of Area %
1050	15	394	No	185.5	152.2	4.7	12.2
	15	418	Yes	190.1	160.1	3.0	5.6
1150	30	337	No	156.8	137.5	11.5	35.7
	30	332	Yes	155.6	132.5	13.0	20.0
1250	90	245	No	116.6	84.2	15.5	34.6
	90	262	Yes	117.9	91.1	8.0	24.5

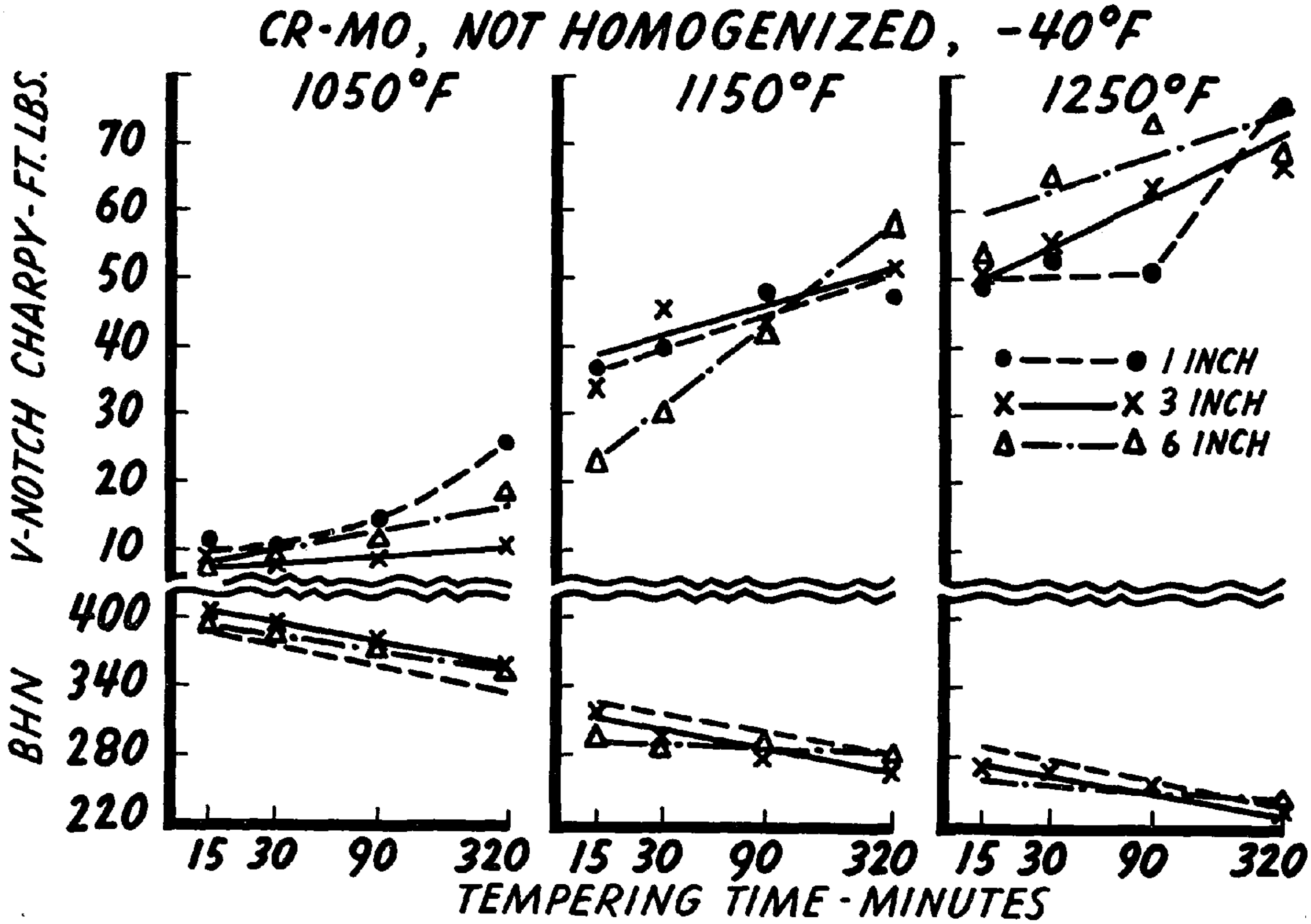


Figure 69—Effect of section thickness on the —40 degrees F Charpy V-notch impact properties of unhomogenized Cr-Mo quenched and tempered cast steel.

low tempering temperatures of 1050 and 1150 degrees F there may be some advantage in using a homogenizing heat treatment for 1-inch thick sections. However, much more data are necessary to definitely establish this point, especially in view of the fact that Figure 71 for the 6-inch sections shows the impact values to be the same regardless of whether a prior homogenization treatment was used.

A comparison of Cr-Mo steel with one of the other steels of the program is illustrated in Figure 72. It will be observed that the impact values for the Mn-Cr-Mo and the Cr-Mo steels are very similar except possibly for the 1050 degrees F tempering temperature. There is, however, general agreement even though the two steels vary considerably in composition.

There was no difference in the microstructures of the quenched and tempered Cr-Mo steels on the basis of whether they received or did not receive a prior homogenization heat treatment. The data indicated that if differences were to be found they would be observed in the microstructures of the 1-inch sections tempered at 1050 degrees F. Figure 73 compares these structures and indicates that they appear the same.

The effect of section size on the microstructure of the Cr-Mo steel is also shown in Figure 73, as is the effect of tempering temperature. The zephiran chloride etch brings out the grain boundary conditions and shows, as these grain boundaries become less distinct, the impact values improve.

Tempering Mn-Ni-Cr-Mo Cast Steels

Tempering studies on the Mn-Ni-Cr-Mo cast steels were undertaken in three section sizes, 1-, 3- and 6-inch. Studies were made at three tempering temperatures for four different times. Impact and tensile properties were obtained on two groups of heat treatments: (1) a homogenization treatment of 1750 degrees F for 320 minutes prior to the quenching heat treatment, and (2) no prior homogenizing heat

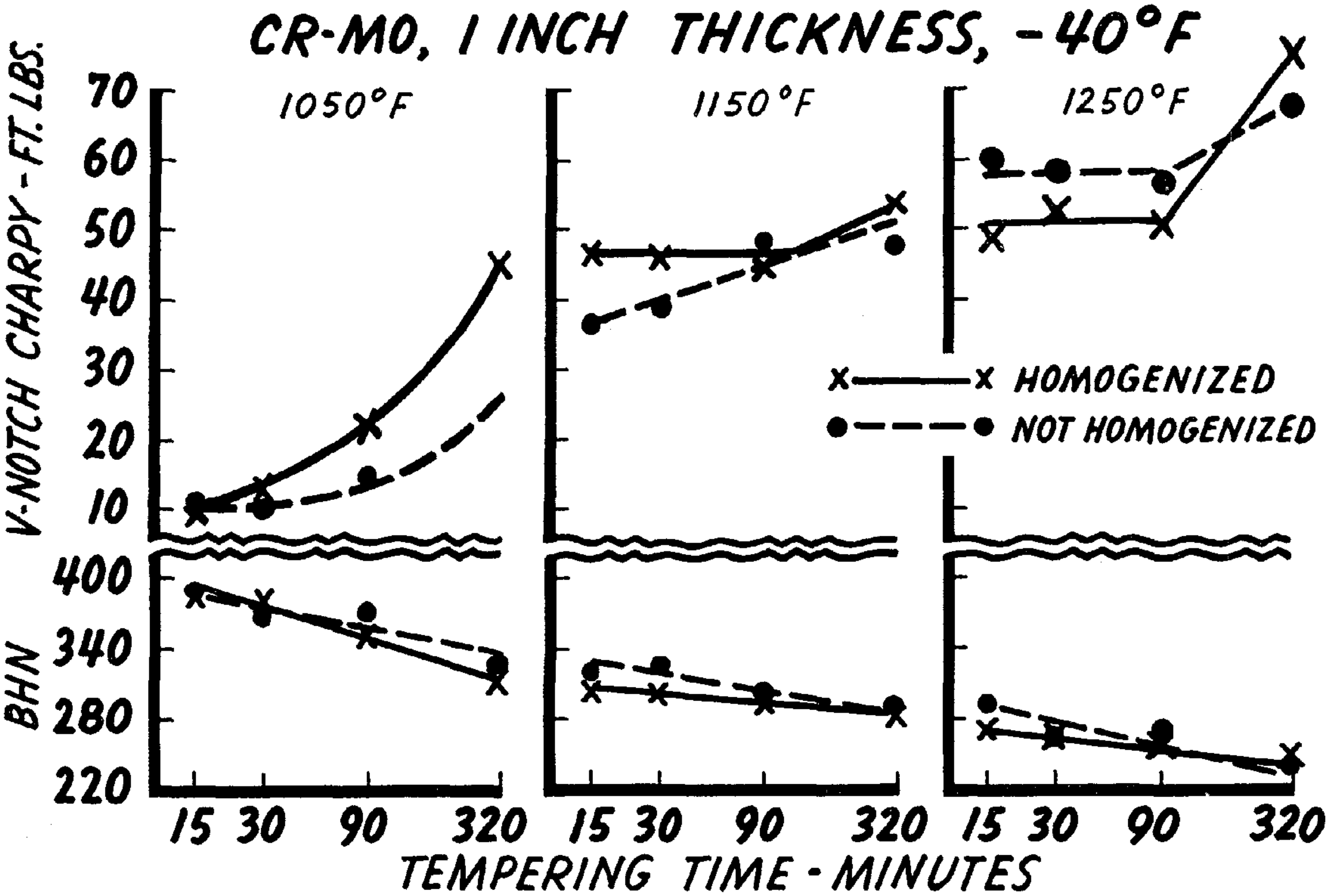


Figure 70—Comparison of a homogenized and unhomogenized prior heat treatment on the Charpy V-notch impact properties at —40 degrees F of quenched and tempered Cr-Mo cast steel - 1-inch section.

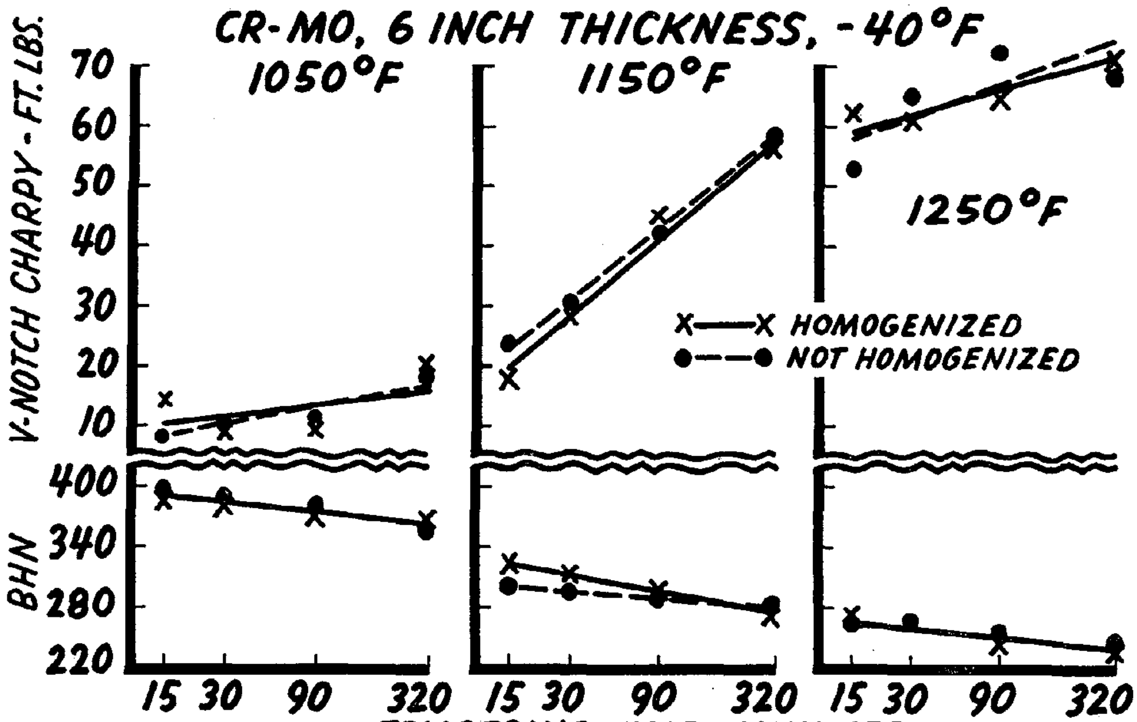


Figure 71—Comparison of homogenized and unhomogenized heat treatment on the Charpy V-notch impact properties at —40 degrees F of quenched and tempered Cr-Mo cast steel - 6-inch section.

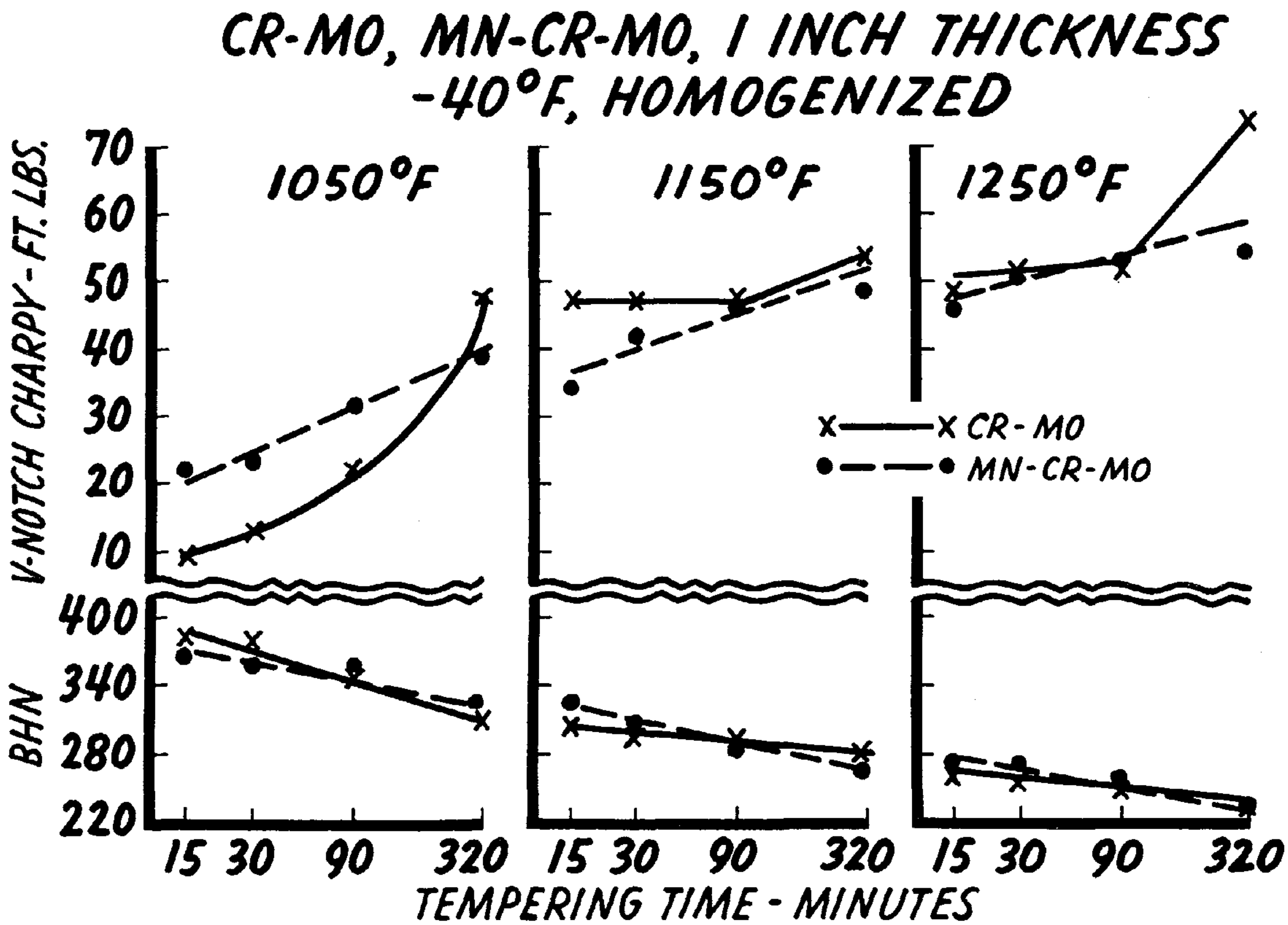


Figure 72—A comparison of the V-notch Charpy impact properties of homogenized Cr-Mo and Mn-Cr-Mo quenched and tempered cast steel of 1-inch sections.

treatment. Again, no effort was made to maintain a constant Brinell hardness value.

A summary of the impact and tensile values for the 1-, 3- and 6-inch sections is given in Tables 35, 36 and 37.

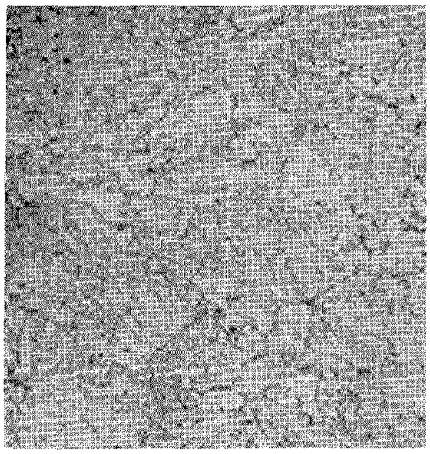
The impact values at a definite tempering temperature for a single section thickness are fairly uniform. The reason for this is that there is not too much variation in the hardness level.

A comparison of the impact values for the 1-inch section of homogenized vs. no homogenization prior heat treatment shows no differences which would permit any preference for one method of heat treatment over the other. The 3-inch sections presented similar results except that the impact values for –80 degrees F after the 1250 degree F temper were somewhat improved when the steel had a prior homogenization treatment.

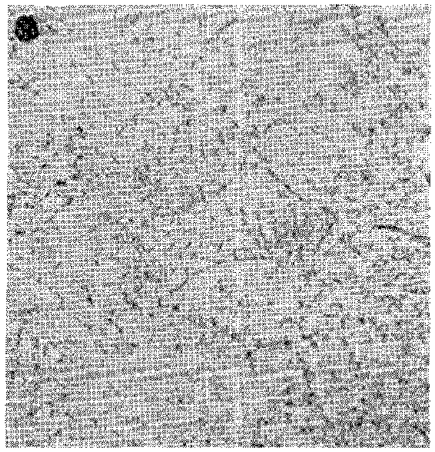
Homogenization of the 6-inch section produced impact values at the 1250 degree F tempering temperature that were better than with no homogenization when tests were made at –40 and –80 degrees F.

A comparison of the 1-, 3- and 6-inch sections is made in Figure 74 as to the effect of tempering time and temperature on the toughness of the Mn-Ni-Cr-Mo cast steel. An interesting item is that the impact values for the 6-inch section in all cases were the best and in most cases the values from the 1-inch section were the poorest. The spread in values was small at the low tempering temperature of 1050 degrees F but became rather wide at 1250 degrees F tempering temperature. In one case a 20 ft-lb. improvement resulted for the 6-inch section over the 1-inch section regardless of holding time. It is true, however, that the hardness values for the 6-inch section were as much as 25 points Brinell below the 1-inch section for the same tempering times.

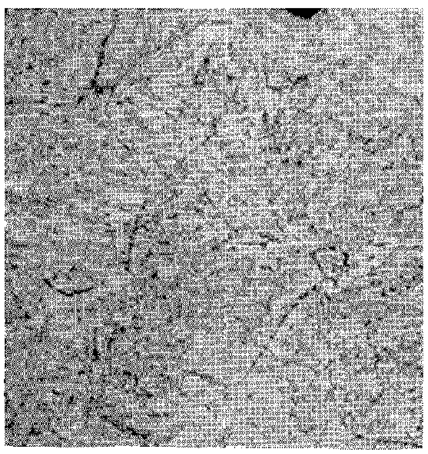
The general level of impact values for this steel is lower than that of the Cr-Mo or the Mn-Cr-Mo. The apparent reason for this is the pronounced precipitation at the grain boundaries that exists in this



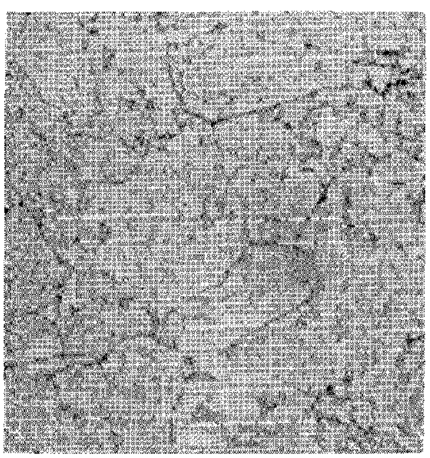
1-inch section. No homogenization; 1050°F temper. 388 BHN 20 ft-lbs.



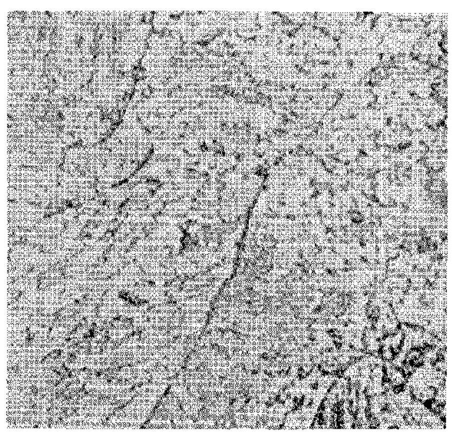
1-inch section. Homogenized. 1050°F temper. 383 BHN 23 ft-lbs.



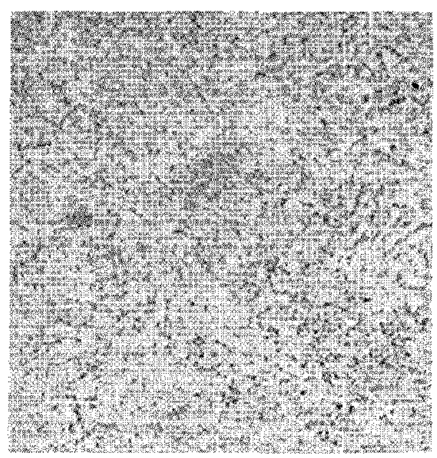
3-inch section. No homogenization; 1050°F temper. 390 BHN 12 ft-lbs.



6-inch section. No homogenization; 1050°F temper. 392 BHN 11 ft-lbs.



6-inch section. No homogenization; 1150°F temper. 295 BHN 47 ft-lbs.



6-inch section. No homogenization; 1250°F temper. 264 BHN 70 ft-lbs.

Figure 73—Cr-Mo quenched and tempered cast steel, picric-zephiran chloride etch. 1000X

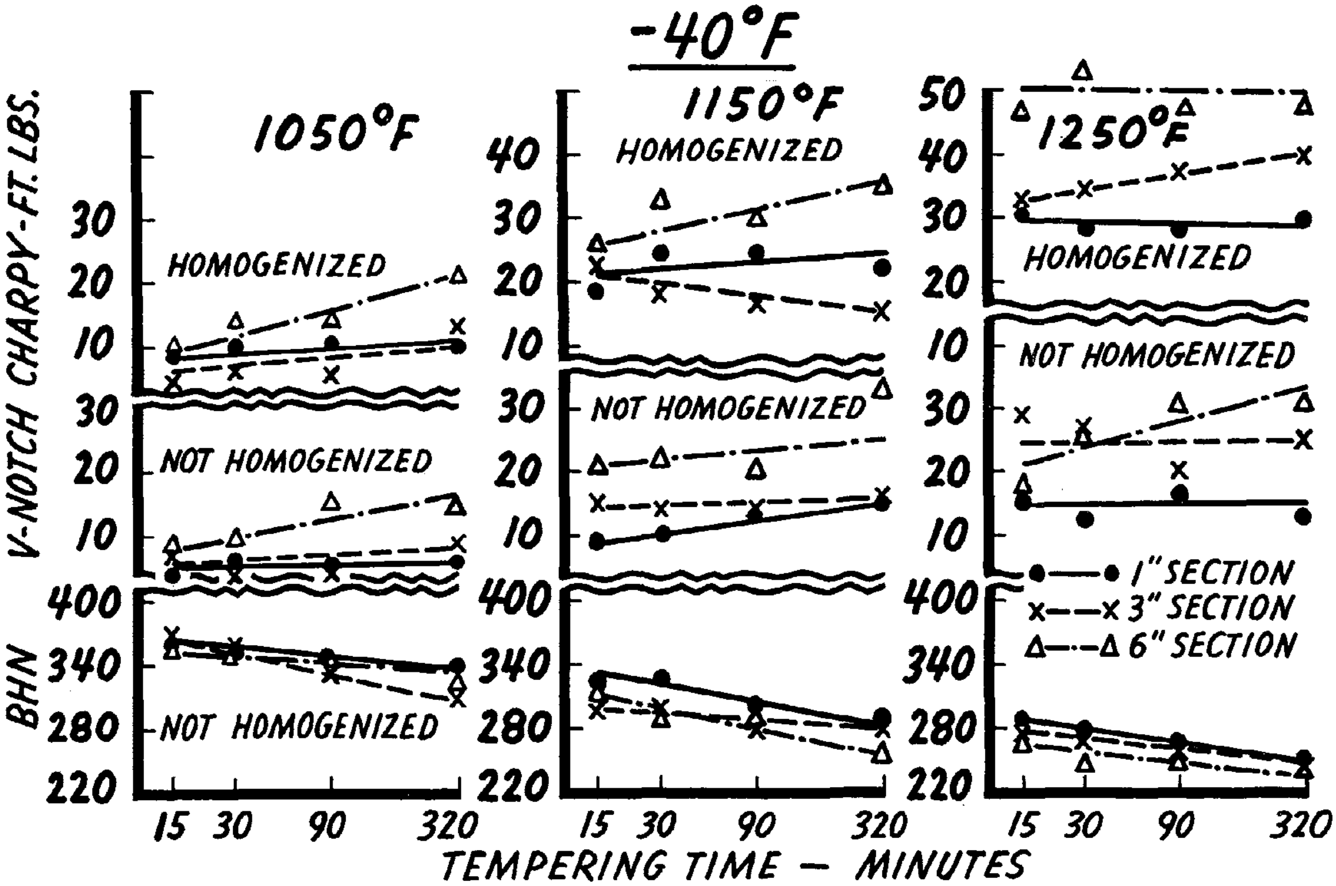


Figure 74—Effect of section thicknesses, 1, 3 and 6 inches, on the −40 degrees F Charpy V-notch impact properties of unhomogenized and homogenized Mn-Ni-Cr-Mo quenched and tempered cast steel.

TABLE 35

Mn-Ni-Cr-Mo Cast Steel - 1-inch Section
The Effect of Tempering Temperature and Time on Toughness and Tensile Properties

HEAT TREATMENT: Homogenize—(1) none; (2) 1750°F for 320 min., air cool
Harden—1650°F, 90 min., water quench
Temper—1050, 1150, 1250°F for 15, 30, 90, 320 min., water quench

Tempering			Charpy V-Notch Impact, ft-lbs.						
			Not Homogenized				Homogenized		
Temperature °F	Time min.	BHN	+70°F	−40°F	−80°F	BHN	+70°F	−40°F	−80°F
1050	15	363	11	4	4	348	17	8	7
	30	348	11	6	5	343	20	9	6
	90	345	12	6	6	335	17	10	6
	320	333	12	6	6	331	19	10	7
1150	15	324	16	9	6	305	26	18	11
	30	323	19	10	6	295	25	24	22
	90	295	26	13	8	293	24	24	19
	320	280	26	15	7	277	28	22	18
1250	15	282	30	25	13	257	40	30	22
	30	273	30	22	15	257	35	28	24
	90	258	35	26	15	254	36	28	19
	320	243	38	23	16	253	39	29	18

Temp. °F	Time min.	BHN	Homo. Treat.	T. S. 1000 psi	Yield 1000 psi	Elongation %	Red. of Area %
1050	30	352	No	168.8	146.3	8.0	22.4
	30	340	Yes	159.3	149.0	3.8	9.2
1150	30	327	No	145.7	127.6	10.5	31.9
	30	311	Yes	146.1	123.5	10.7	25.3
1250	30	269	No	125.4	102.7	14.8	41.2
	30	277	Yes	125.1	105.3	15.5	43.0

TABLE 36

Mn-Ni-Cr-Mo Cast Steel - 3-inch Section
The Effect of Tempering Temperature and Time on Toughness and Tensile Properties

HEAT TREATMENT: Homogenize—(1) none; (2) 1750°F for 320 min., air cool
Harden—1650°F, 90 min., water quench
Temper—1050, 1150, 1250°F for 15, 30, 90, 320 min., water quench

Tempering		Charpy V-Notch Impact, ft-lbs.							
		Not Homogenized				Homogenized			
Temperature °F	Time min.	BHN	+70°F	−40°F	−80°F	BHN	+70°F	−40°F	−80°F
1050	15	361	12	5	4	352	9	4	3
	30	357	11	4	5	344	12	6	4
	90	332	16	5	3	325	18	6	5
	320	298	17	9	6	319	18	13	11
1150	15	293	16	15	10	307	24	22	21
	30	294	22	14	11	298	23	18	14
	90	277	27	14	9	287	30	17	16
	320	277	29	16	9	276	28	15	14
1250	15	271	40	39	27	266	42	32	30
	30	265	41	36	26	264	45	34	38
	90	255	43	29	25	253	42	37	36
	320	243	47	35	30	241	45	40	33

Temp. °F	Time min.	BHN	Homo. Treat.	T. S. 1000 psi	Yield 1000 psi	Elongation %	Red. of Area %
1050	90	358	No	161.0	141.0	5.5	13.5
	90	351	Yes	155.8	139.5	5.5	9.9
1150	90	302	No	130.3	119.3	3.0	10.8
	15	340	Yes	142.8	132.9	2.5	10.1
1250	90	269	No	122.0	102.3	12.3	24.5
	90	269	Yes	123.1	103.3	14.7	38.0

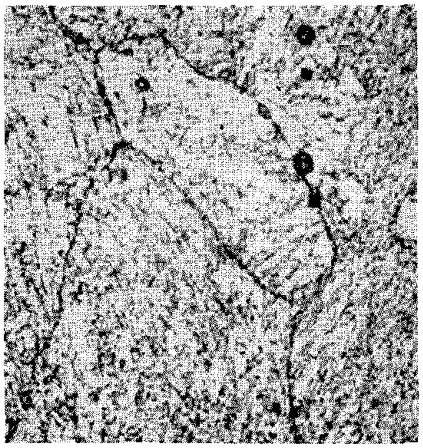
TABLE 37

Mn-Ni-Cr-Mo Cast Steel - 6-inch Section
The Effect of Tempering Temperature and Time on Toughness and Tensile Properties

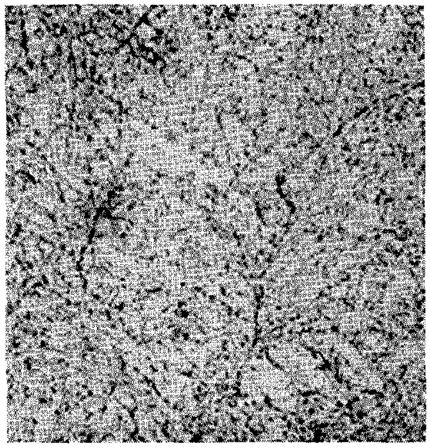
HEAT TREATMENT: Homogenize—(1) none; (2) 1750°F for 320 min., air cool
Harden—1650°F, 90 min., water quench
Temper—1050, 1150, 1250°F for 15, 30, 90, 320 min., water quench

Tempering		Charpy V-Notch Impact, ft-lbs.							
		Not Homogenized				Homogenized			
Temperature °F	Time min.	BHN	+70°F	−40°F	−80°F	BHN	+70°F	−40°F	−80°F
1050	15	352	21	8	5	352	17	9	8
	30	344	24	9	7	356	25	14	8
	90	344	28	15	12	323	33	14	10
	320	327	24	15	9	327	39	21	16
1150	15	300	28	21	14	280	47	25	16
	30	286	33	22	19	271	45	32	30
	90	283	33	20	15	286	39	30	26
	320	254	51	34	26	271	42	35	29
1250	15	264	39	27	17	268	50	45	44
	30	245	50	36	23	247	57	53	42
	90	237	53	40	25	253	48	46	44
	320	243	55	40	32	237	52	47	48

Temp. °F	Time min.	BHN	Homo. Treat.	T. S. 1000 psi	Yield 1000 psi	Elongation %	Red. of Area %
1050	15	364	No	156.4	135.4	9.0	21.8
	15	340	Yes	162.4	144.9	8.0	19.6
1150	30	298	No	141.0	122.3	8.5	21.6
	30	304	Yes	139.3	117.9	9.5	26.6
1250	30	255	No	115.0	94.6	7.0	16.7
	30	265	Yes	117.6	96.7	13.2	27.8

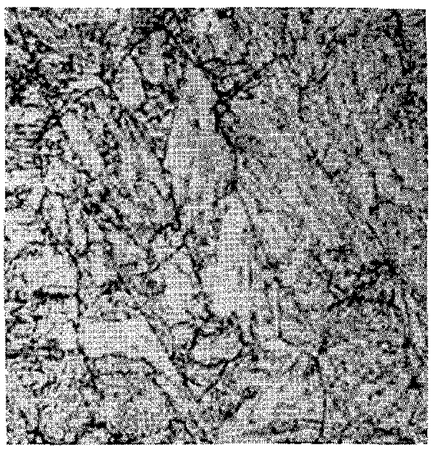


1-inch section. No homogenization; 1150°F temper. 294 BHN 10 ft-lbs.

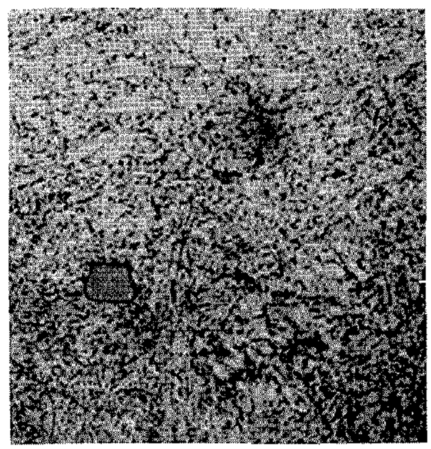


1-inch section. No homogenization; 1250°F temper. 267 BHN 30 ft-lbs.

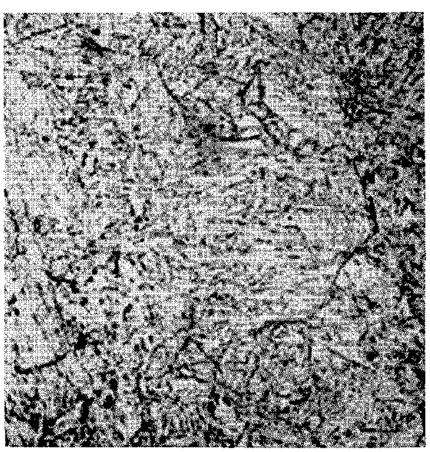
3-inch section. No homogenization; 1050°F temper. 362 BHN 12 ft-lbs.



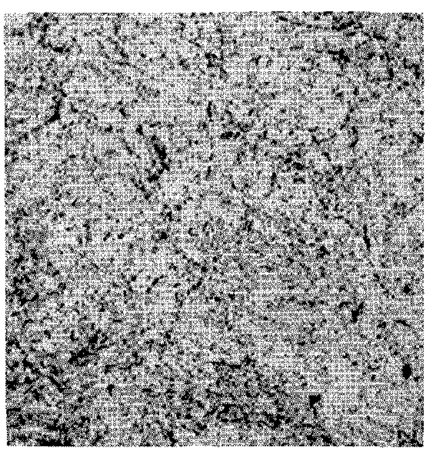
3-inch section. No homogenization; 1150°F temper. 268 BHN 26 ft-lbs.



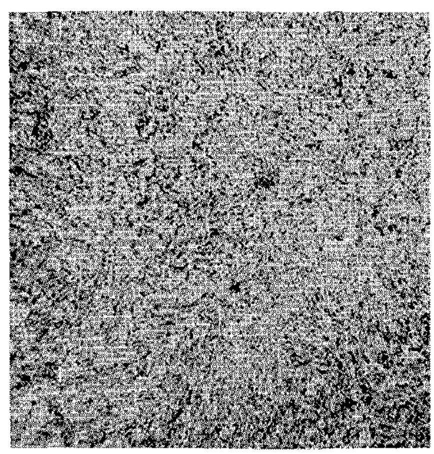
3-inch section. No homogenization; 1250°F temper. 258 BHN 41 ft-lbs.



6-inch section. Homogenized; 1050°F temper. 336 BHN 28 ft-lbs.



6-inch section. Homogenized; 1150°F temper. 262 BHN 31 ft-lbs.



6-inch section. Homogenized; 1250°F temper. 240 BHN 57 ft-lbs.

Figure 75—Mn-Ni-Cr-Mo quenched and tempered cast steel, picric-zephiran chloride etch. 1000X

steel. This is apparently a condition of the manufacturing process for this particular steel. Other steels of a similar composition give excellent impact properties at lower temperatures.

It is interesting to observe the relation between microstructure, hardness and impact properties as illustrated in Figure 75. It will be observed that values of over 50 ft-lbs. are obtained only when the grain boundary condition is not evident. Even though the steel is homogenized for 5-1/3 hours prior to the quenching treatment the grain boundary condition is evident for the 1050 and 1150 tempering temperatures. Thus, homogenization in itself does not produce a uniform structure. Further, tempering to a high temperature is necessary for the best impact results.

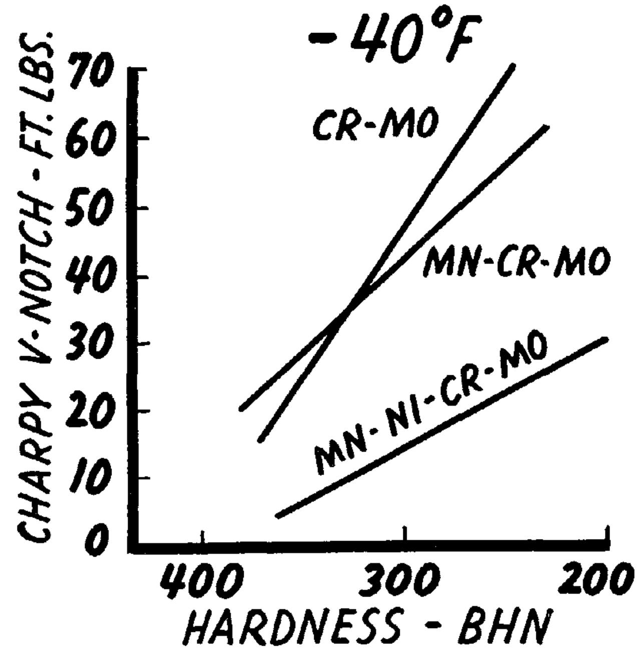


Figure 76—Notched-bar impact properties of quenched and tempered low-alloy cast steels vs. hardness

Summary of Tempering at Variable Hardnesses

The effect of tempering temperature and time on the toughness properties of quenched and tempered cast steels may be summarized as follows:

1—Heating quenched steel at any tempering temperature will result in a reduction in the hardness of the steel as the heating time is prolonged.

2—The notched bar impact properties of cast steel increase as the hardness decreases. This condition is a straight line function; however, the rate of increase may or may not be similar (see Figure 76) and probably will vary from one heat of steel to another, depending on manufacturing conditions.

3—The ductility of the steel improves as the tempering time increases at a specified tempering temperature. The reason for this is that the hardness of the steel is decreasing.

4—Time of heating at the tempering temperature can be very short. A period of 15 to 30 minutes is sufficient if the tempering temperature is 1050 degrees F or above.

5—The time at tempering temperature is not dependent on the thickness of the section of the casting being tempered.

6—A comparison of the value of a homogenization treatment and no homogenization treatment prior to quenching and tempering shows the following:

a. Carbon cast steel—toughness values are the same;

b. Mn-B cast steel—toughness values are the same;

c. Mn-Cr-Mo cast steel—a prior homogenization treatment produced the best toughness values;

d. Cr-Mo cast steel—no clear cut trend for a prior homogenization treatment;

e. Mn-Ni-Cr-Mo cast steel — toughness values were improved at low temperature in heavy sections when homogenizing prior treatment was employed.

7—The studies point to the fact that if, in the manufacturing process of steel castings, it is possible to dispense with a heat treatment prior to the quenching and tempering treatment it would be advisable to do so from the standpoint of economics and conservation of time. The prior homogenization or normalizing heat treatment does not materially improve the strength, toughness or ductility properties at a constant hardness level for most steels (see item 6 above).

8—Excellent impact values at normal and low temperatures can be obtained by cast steels receiving a quenching and tempering treatment.

SECTION IX
THE EFFECT OF TEMPERING ON TOUGHNESS AT A CONSTANT HARDNESS

Section VIII of this report showed that if a quenched steel was tempered at any chosen temperature the hardness of the steel would decrease as the time at temperature was extended. Therefore, one could not compare the impact properties of short tempering times with those of long tempering times at a definite temperature because the hardness values would be different.

The data from Section VIII, for the most part, was not sufficiently overlapping so that a plotting of the data could result in toughness values being picked off at equal hardnesses. The only way in which it would be possible to determine whether short time heat treatments developed toughness values equivalent to those secured by tempering at a temperature for a long period of time would be to restudy the steels with the idea of holding the hardness at a constant value and changing the tempering temperature and time so as to arrive at one hardness level.

For example, if a constant hardness of 250 Brinell were selected for the tempered hardness of a quenched steel then in one case a high tempering temperature at a short time would be employed as well as a low temperature for a very long time. Intermediate temperatures and times would also result in hardnesses of 250 Brinell.

Another group of steels, somewhat similar to the original set, was produced. The composition of these steels is given in Table 38.

The section thickness and the hardness levels to be attained after tempering were selected as follows:

Mn-Cr-Mo	1-, 3- and 6-inch sections at 250 BHN
Ni-Cr-Mo	1- and 3-inch sections at 250 BHN; and 1-inch section at 320 BHN
Cr-Mo	3- and 6-inch sections at 250 BHN
Mn-Ni-Cr-Mo	3- and 6-inch sections at 250 BHN

TABLE 38

Composition of Cast Steels for Constant Hardness Study after Quench and Tempering

Class	Type†	C	Mn	Ni	Cr	Mo
Ni-Cr-Mo	AE	0.30	0.96	0.76	0.77	0.43
Mn-Cr-Mo #2	BE	0.30	1.47	—	0.72	0.48
Cr-Mo	BOH	0.31	0.60	—	2.31	0.56
Mn-Ni-Cr-Mo #4	AOH	0.32	1.20	0.87	1.00	0.47

†A = Acid; B = Basic; E = Electric; OH = Open-hearth

The test blocks used for the 1-inch section studies were 1 x 4½ x 10-inch multiple blocks. The test blocks used for the 3- and 6-inch sections for all steels except the Cr-Mo were of 1¾ x 2¾ x 12-inch dimension. They were machined into 1-inch round bars and inserted into the center of 3 x 9 x 9 and 6 x 14 x 14-inch carrier blocks and heat treated in the blocks.

The test bars from the Cr-Mo were 1-inch rounds machined from the 3 x 9 x 9-inch and 6 x 14 x 14-inch blocks and inserted into the center of 3- and 6-inch carrier blocks for heat treatment.

The heat treatments used in this section consisted of no prior homogenization treatment. In other words, the steels were in the non-homogenized condition. They were heated to the quenching temperature quickly and held at this temperature for a short period of time and quenched in water. They were then reheated to five different tempering temperatures for various times to permit a constant hardness of 250 Brinell and then quenched in water. The impact specimens were hardness tested after fracture and the hardnesses were to be maintained within the following range:

250 BHN—24 Rockwell C (range 22-26)
320 BHN—34 Rockwell C (range 33-35.5)

Two Charpy V-notch impact specimens were tested at +70 and three specimens at –40 degrees F for each time-temperature hardness. The property values obtained are given in Tables 39 to 42, and shown in Figures 77 to 80.

Photomicrographs of the structures of three of the alloy cast steels are shown in Figures 81, 82 and 83. These water quenched alloy cast steels were all tempered to about 250 Brinell. The microstructures of steel tempered at short times at high temperatures are compared with long tempering times at lower temperatures. Also, structures of specimens taken from different section sizes are compared.

A review of all the illustrations will show that all microstructures are very similar; they consist of tempered martensite. There is a tendency for the former acicular structure to be apparent in the short time tempering group of micrographs. The 3-inch and 6-inch sections are very comparable in appearance. The 1-inch section has a slightly more acicular appearance but the uniformly distributed

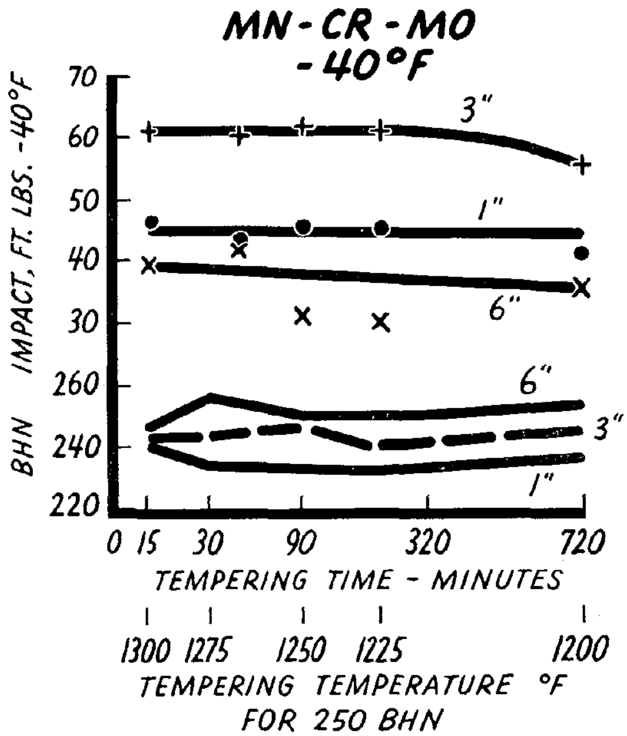


Figure 77—Charpy V-notch impact properties of 1-, 3- and 6-inch sections of Mn-Cr-Mo cast steel at —40 degrees F under conditions of constant hardness with varying tempering times and temperatures. Steel water quenched; no prior homogenizing treatment

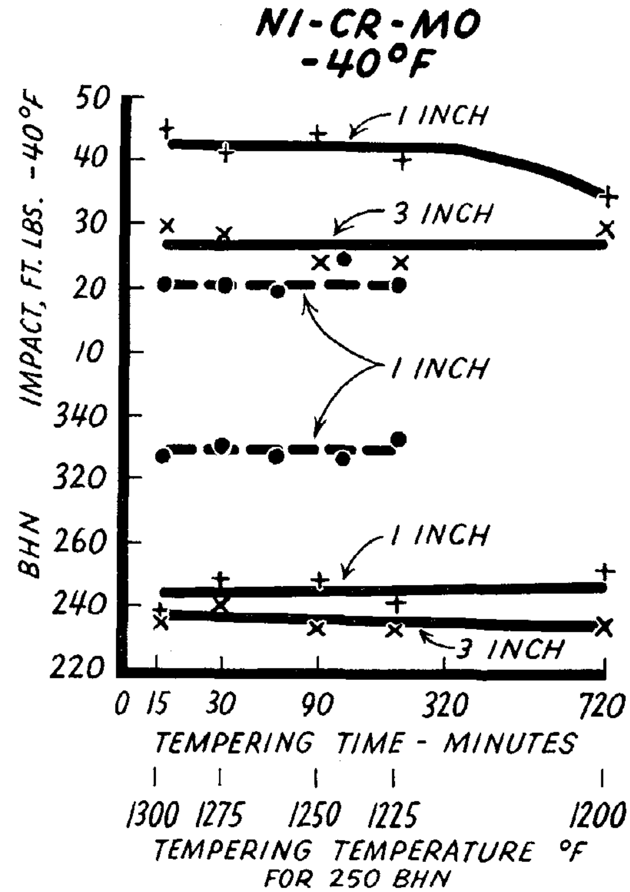


Figure 78 Charpy V-notch impact properties at —40 degrees F for 1- and 3-inch sections of Ni-Cr-Mo cast steel under conditions of constant hardness at 250 and 320 BHN for various tempering times and temperatures. Steel water quenched; no prior homogenizing treatment

TABLE 39

Ni-Cr-Mo Cast Steels Tempered to a Constant Hardness

HEAT TREATMENT: No homogenization
Harden—1650°F for 30 minutes, water quench
Temper—(1) 250 BHN, water quench
(2) 320 BHN, water quench

Temper		Charpy V-Notch Impact, ft. lbs.						Temper			Charpy V-Notch Impact, ft. lbs.		
		1-inch Section			3-inch Section						1-inch Section		
Temp. °F	Time min.	BHN	+70°F	–40°F	BHN	+70°F	–40°F	Temp. °F	Time min.	BHN	+70°F	–40°F	–80°F
1300	18	237	46	44	237	56	28	1150	15	327	29	20	18
1275	25	247	44	41	240	58	27	1125	25	330	28	20	17
1250	90	247	43	44	233	53	24	1100	60	327	27	19	18
1225	4 hrs.	240	42	40	233	54	24	1075	110	327	30	25	20
1200	12 hrs.	250	41	34	233	53	29	1050	150	332	28	20	19

Tensile Properties - 1-inch Section

Temp. °F	Time min.	BHN	Tensile Strength psi	Yield Point psi	Elongation % in 2"	R. A. %
1300	18	241	115,650	87,200	13.3	32.8
1200	240	255	125,700	103,500	12.7	33.2
1100	60	332	158,600	146,600	9.0	38.4
1075	110	327	157,000	145,000	9.7	38.0

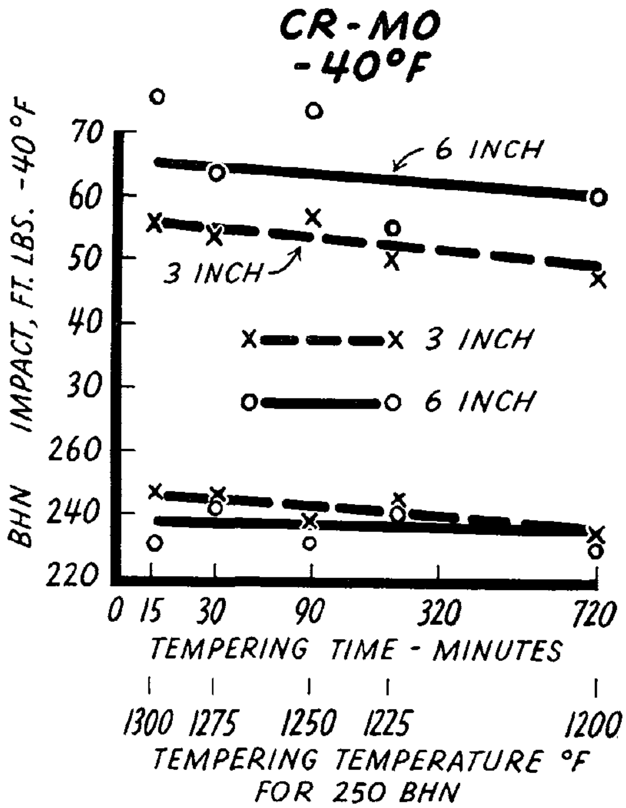


Figure 79—Charpy V-notch impact properties at −40 degrees F for 3- and 6-inch sections of Cr-Mo cast steel under conditions of constant hardness at 250 BHN for various tempering times and temperatures. Steel water quenched; no prior homogenizing treatment

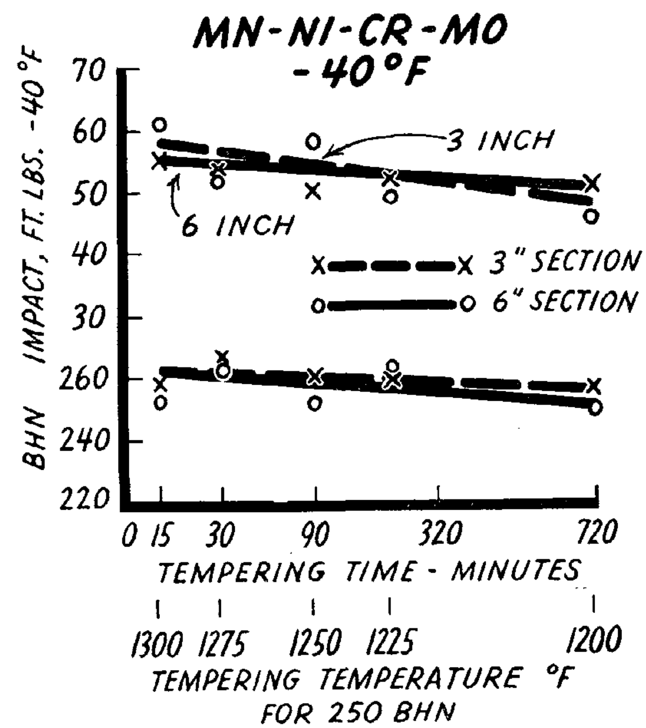


Figure 80—Charpy V-notch impact properties at −40 degrees F for 3- and 6-inch sections of Mn-Ni-Cr-Mo cast steel under conditions of constant hardness at 250 BHN for various tempering times and temperatures. Steel water quenched; no prior homogenizing treatment

TABLE 40

Mn-Cr-Mo Cast Steels Tempered to a Constant Hardness

HEAT TREATMENT: No Homogenization
Harden—1650°F for 30 minutes, water quench
Temper—250 BHN, water quench

Temper		Charpy V-Notch Impact, ft. lbs.								
		1-inch Section			3-inch Section			6-inch Section		
Temp. °F	Time min.	BHN	+70°F	−40°F	BHN	+70°F	−40°F	BHN	+70°F	−40°F
1300	18	243	54	46	245	66	62	240	70	39
1275	25	245	49	44	257	62	61	234	64	43
1250	90	247	49	45	250	68	63	232	64	31
1225	4 hrs.	240	54	45	250	64	62	240	64	30
1200	12 hrs.	252	50	41	245	63	54	236	56	35

Tensile Properties—1- and 6-inch Sections

Temp. °F	Time min.	Section Thickness in.	BHN	Tensile Strength psi	Yield Point psi	Elongation % in 2"	R. A. %
1300	18	1	241	116,600	93,500	16.8	44.9
1200	240	1	255	123,000	93,000	14.7	41.0
1300	18	6	241	107,000	79,000	14.5	39.6
1200	12 hrs.	6	241	110,600	86,000	18.2	47.7

structure of the tempered martensite without the presence of free ferrite permits the excellent Charpy V-Notch impact values as recorded in Tables 39 to 42. The steels are presented in these tables in their order of increasing hardenability. Table 39 is a low hardenable steel and Table 42 presents values from the steel of the highest hardenability of the steels studied.

The Ni-Cr-Mo cast steel was studied in two section sizes, 1 and 3 inches at 250 Brinell and 1 inch at 320 Brinell (Table 39 and Figure 78). The impact values at normal and low temperatures were fairly constant. Only one value at –40 degrees F for 1-inch section was out of line and this should have been rechecked. The room temperature values for the 3-inch section were better than those for the 1-inch section. This is because of the coupon design of these two sections. The low temperature impact values for the 3-inch section are much below those of the 1-inch section because this steel does not have the thorough hardening qualities for a 3-inch section.

Studies at the two hardness levels show that a short time heat treatment will produce the same impact values as a long time tempering treatment provided a constant hardness is maintained. The same can also be said concerning the tensile properties. The reduction of area values for the 250 BHN

TABLE 41

Cr-Mo Cast Steel Tempered to a Constant Hardness

HEAT TREATMENT: No Homogenization
Harden—1650°F for 30 minutes, water quenched
Temper—250 BHN water quenched

Tempering		Charpy V-Notch Impact, ft. lbs.					
		3-inch Section			6-inch Section		
Temperature °F	Time min.	BHN	+70°F	–40°F	BHN	+70°F	–40°F
1300	18	246	61	56	230	76	76
1275	25	244	61	54	245	66	64
1250	90	238	62	57	232	82	74
1225	4 hrs.	246	58	50	240	71	55
1200	12 hrs.	234	63	47	230	79	60

Tensile Properties—6-inch Section

Temp. °F	Time min.	BHN	Tensile Strength psi	Yield Point psi	Elongation % in 2"	R. A. %
1300	18	228	107,250	82,700	19.0	48.6
1200	12 hrs.	241	101,500	82,500	14.0	36.2

TABLE 42

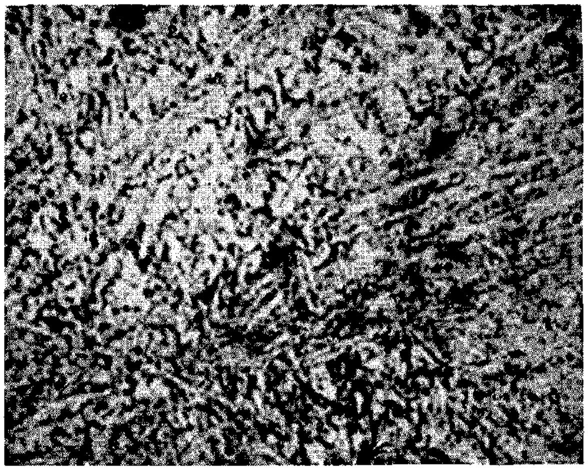
Mn-Ni-Cr-Mo Cast Steel Tempered to a Constant Hardness

HEAT TREATMENT: No Homogenization
Harden—1650°F for 30 minutes, water quenched
Temper—250 BHN, water quenched

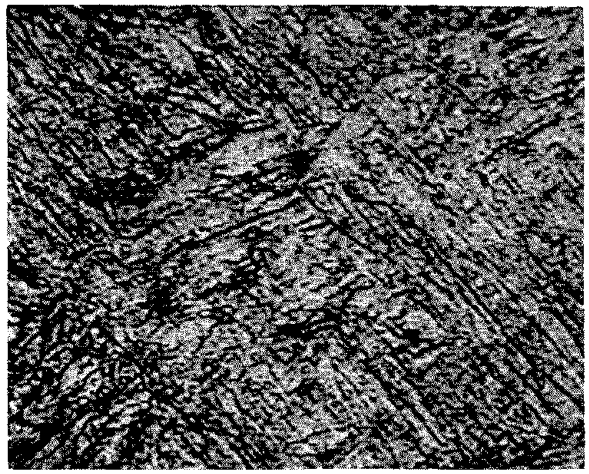
Tempering		Charpy V-Notch Impact, ft. lbs.					
		3-inch Section			6-inch Section		
Temperature °F	Time min.	BHN	+70°F	–40°F	BHN	+70°F	–40°F
1300	18	258	60	55	252	65	61
1275	25	266	57	54	263	56	52
1250	90	260	56	50	252	60	58
1225	4 hrs.	260	58	52	263	57	49
1200	12 hrs.	256	54	51	250	55	46

Tensile Properties—6-inch Section

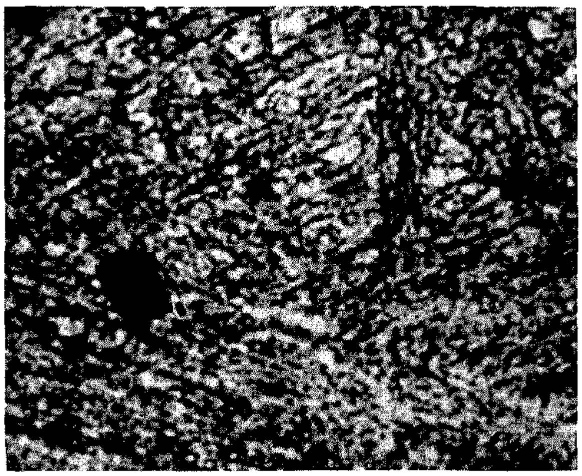
Temp. °F	Time min.	BHN	Tensile Strength psi	Yield Point psi	Elongation % in 2"	R. A. %
1300	18	269	129,400	83,900	15.0	37.3
1200	12 hrs.	255	123,200	101,500	15.5	45.0



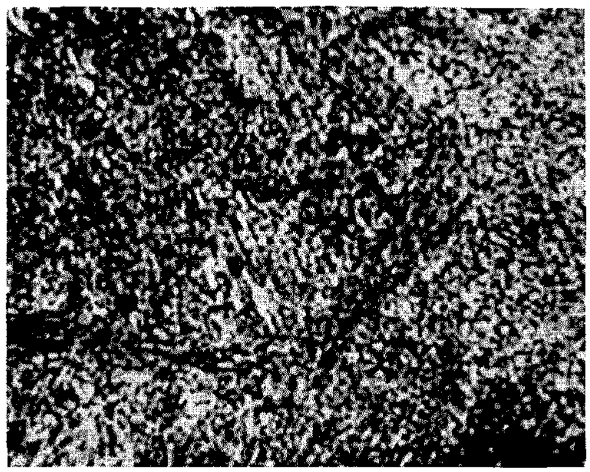
a. 1-inch section. Tempered 90 minutes at 1250 degrees F



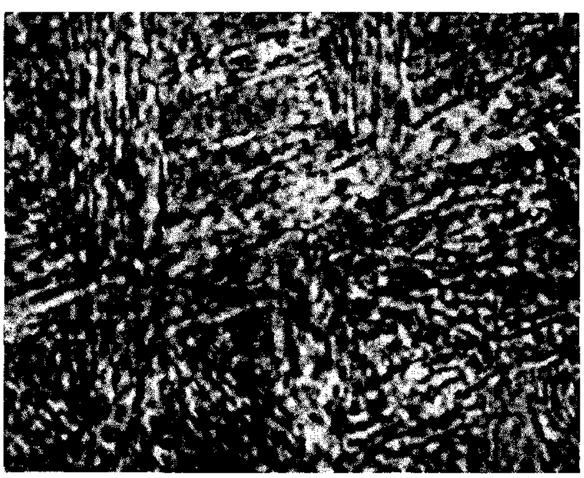
b. 1-inch section. Tempered 240 minutes at 1200 degrees F



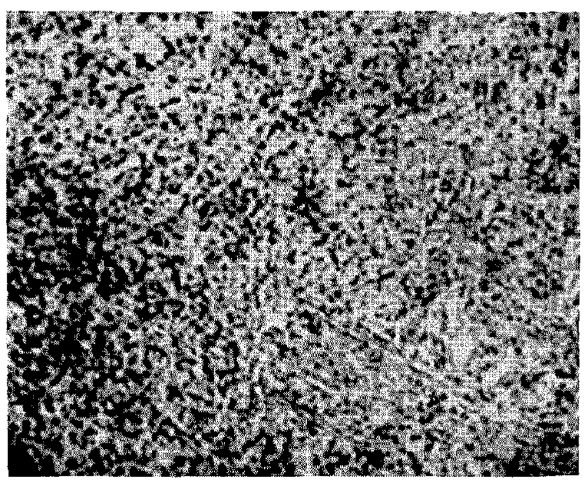
c. 3-inch section. Tempered 18 minutes at 1300 degrees F



d. 3-inch section. Tempered 12 hours at 1200 degrees F

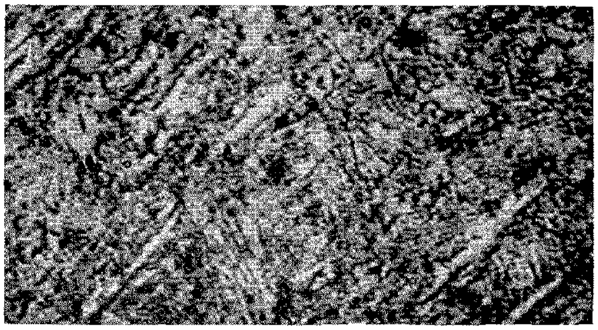


e. 6-inch section. Tempered 18 minutes at 1300 degrees F

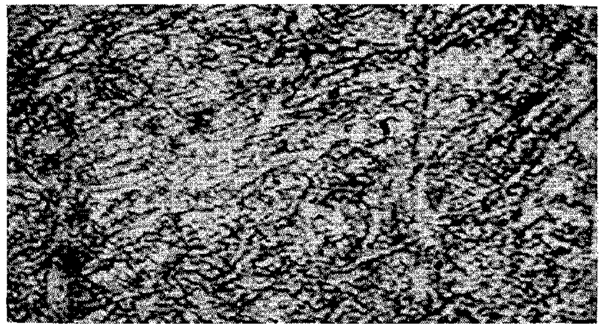


f. 6-inch section. Tempered 12 hours at 1200 degrees F

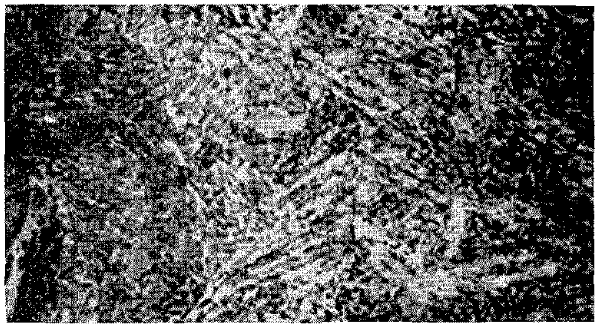
Figure 81 Mn-Cr-Mo cast steel tempered to a constant hardness of 250 Brinell following water quenching from 1650 degrees F for 30 minutes. Picral etch. 1000X



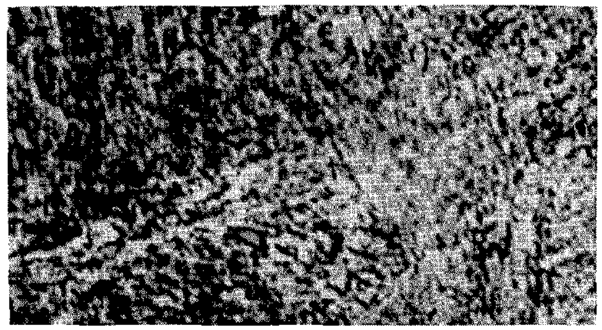
a. 1-inch section. Tempered 18 minutes at 1300 degrees F



b. 1-inch section. Tempered 240 minutes at 1200 degrees F



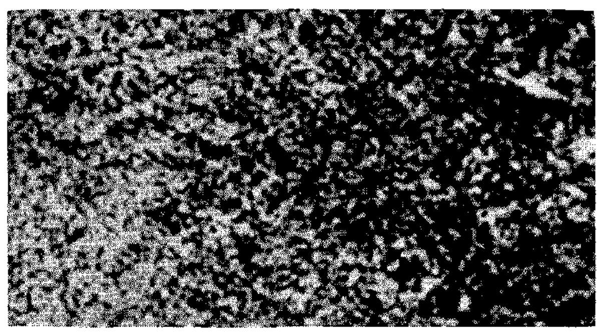
c. 3-inch section. Tempered 18 minutes at 1300 degrees F



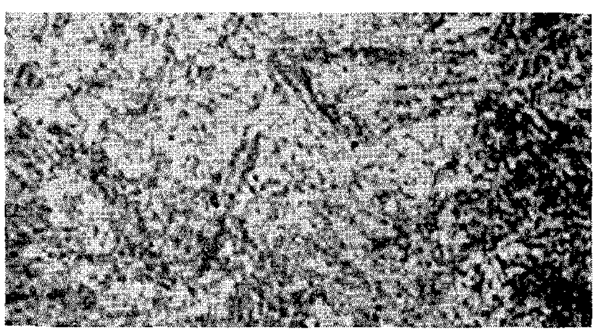
d. 3-inch section. Tempered 12 hours at 1200 degrees F

Figure 82—Ni-Cr-Mo cast steel tempered to a constant hardness of 250 Brinell following water quenching from 1650 degrees F for 30 minutes. Picral etch. 1000X

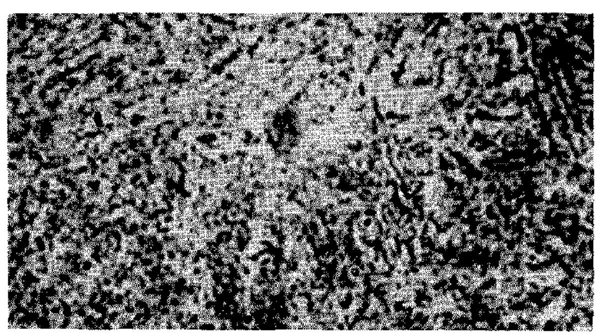
a. 3-inch section. Tempered 18 minutes at 1300 degrees F



b. 3-inch section. Tempered 12 hours at 1200 degrees F



c. 6-inch section. Tempered 18 minutes at 1300 degrees F



d. 6-inch section. Tempered 12 hours at 1200 degrees F

Figure 83—Cr-Mo cast steel tempered to a constant hardness of 250 Brinell following water quenching from 1650 degrees F for 30 minutes. Picral etch. 1000X

treatment are somewhat out of line, apparently from testing inconsistency.

All three sections (1-, 3- and 6-inch) were studied in Mn-Cr-Mo cast steel (Table 40 and Figure 77). The +70 degrees F impact properties for the 3- and 6-inch sections are very similar and superior to those of the 1-inch section. This same condition holds true for the –40 degrees F testing of impact specimens from the 1- and 3-inch sections. The 6-inch section is too great for the hardenability of this steel so the impact values drop sharply. Thus both coupon design and hardenability are factors in producing changes in toughness values. However, the impact values were very constant even though a short holding time was employed in comparison to the long tempering times at low tempering temperatures.

All of the tensile properties can be considered as being nearly identical regardless of section size or time and temperature of tempering. A comparison of the Ni-Cr-Mo and the Mn-Cr-Mo cast steels in the 1-inch section size, which is the only section size that can be compared because of hardenability considerations, shows that at –40 degrees F the impact values are very similar. The room temperature impact properties are slightly improved for the Mn-Cr-Mo steel.

The Cr-Mo cast steel was studied in the 3- and 6-inch sections at 250 Brinell (Table 41 and Figure 79). The –40 degrees F impact properties of this steel were excellent for both section thicknesses. The data can be interpreted as showing a fall-off in toughness with increasing tempering time at a constant hardness.

The tensile properties of the Cr-Mo 6-inch steel section were comparable with those of the 6-inch section of the Mn-Cr-Mo steel.

The steel having the highest hardenability, the Mn-Ni-Cr-Mo cast steel, was also studied in the 3- and 6-inch section sizes (Table 42 and Figure 80). This steel also showed a tendency to drop off in toughness at –40 degrees F as the tempering time increased while maintaining a constant hardness level. This condition was also evident when testing was carried on at +70 degrees F.

Summary of Toughness at a Constant Hardness

The effect of the tempering at 1075 degrees F and above of quenched low-alloy cast steels on toughness at a constant hardness level can be summarized from the test studies as follows:

1—The tempering time and temperature of cast steel can be varied to produce a constant hardness. If this is done there is no increase in toughness properties at normal or low temperatures as the tempering time increases such as was found in Section VIII where hardness was not a constant value.

2—Short time tempering of quenched low-alloy cast steel produced toughness values equal to or greater than long tempering times when hardness values are constant.

3—Changes in section thicknesses from 1 to 6 inches do not adversely affect the use of the short time tempering treatment.

4—The microstructures of steels of varying section size and varying time-temperature tempering relationships are comparable and consist of tempered martensite.

5—The high hardenable steels of the Cr-Mo and Mn-Ni-Cr-Mo types tend to show decreasing toughness values with increasing tempering time at constant hardness.

6—The lower hardenable steels, such as the Ni-Cr-Mo and Mn-Cr-Mo types show relatively constant toughness values with increasing tempering time at constant hardness.

7—The tensile properties of the cast steel are similar at constant hardnesses regardless of the length of tempering time. The heavier section thicknesses show some fall-off in properties.

SECTION X
DETERMINATION OF THE IMPORTANCE OF DOUBLE TEMPERING ON TOUGHNESS

The steel casting heat treating literature contains, from time to time, references to the effect that casting properties are improved if the tempering operation is repeated twice following the quenching treatment. It also has been suggested that improved properties can be secured if a double tempering operation follows a normalizing heat treatment. It should be indicated that there is but little information on the effect of double tempering on the toughness of cast steels when measured by notched bar impact tests at low temperatures.

A short study was programmed for this research to check on the possibility of improving the toughness of quenched and tempered cast steels receiving short time heat treatments by employing an additional tempering treatment. Again, it was decided to ascertain what effect the double tempering treatment would have on section size and, therefore, studies were made on 1-, 3- and 6-inch sections for two cast steels. Two other steels were studied at two section sizes.

Mn-B and Mn-Cr-Mo Double Tempered

The impact and tensile properties of Mn-B and Mn-Cr-Mo cast steels were determined following a short homogenization treatment, quench, and two short tempering treatments. The properties for both 1- and 3-inch sections are given in Table 43.

It will be observed that there is some variation in the hardness of the steels but these values are sufficiently close so that the single and double tempering treatments can be compared as to toughness and tensile properties. Both steels in the 1-inch section size showed the same toughness values and indicated that the additional tempering treatment was of no value. The tensile tests indicated a drop off in the reduction of area values for the double tempering treatment. There is no particular reason for this condition. At least it should not be considered that the double tempering treatment produces this condition. In fact, the 3-inch section of the Mn-B steel, after double tempering, shows a high reduction of area value.

The toughness values of the 3-inch sections for both single and double tempering are very close and again it can be said that the added tempering treatment did not improve the toughness values of these steels. The tensile properties of the 3-inch Mn-B steel section are considerably out of line. No observable reason is suggested for this variation.

A series of photomicrographs is illustrated in Figure 84 taken from the Mn-Cr-Mo steel. There are no differences between the single and double tempering treatments. The greatest difference comes between the microstructures of the 1- and 3-inch sections, as would be expected.

Cr-Mo and Mn-Ni-Cr-Mo Cast Steel, Double Tempered

The impact and tensile properties of the Cr-Mo and the Mn-Ni-Cr-Mo cast steels are compared after a single quench and tempering treatment with those receiving a quench and double tempering treatment. Short time heat treatments were employed as well as long time treatments. Property values obtained are presented in Table 44.

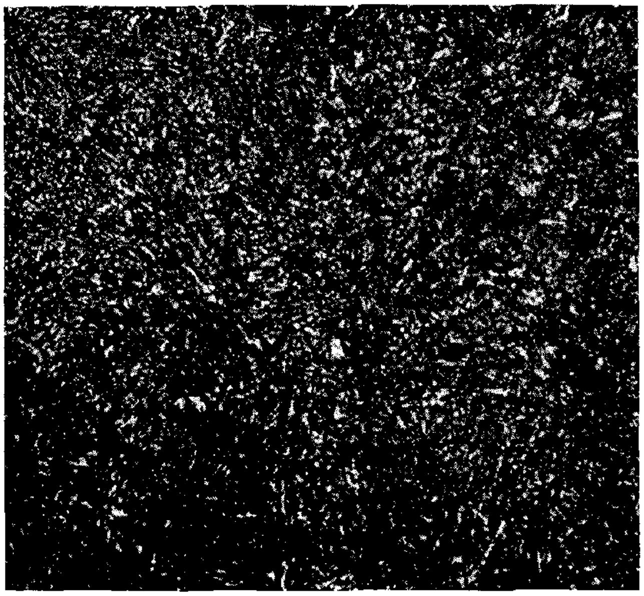
A quick comparison of the toughness values for the single and double tempering heat treatments will disclose that the impact values are, in general, of the same order. Also, the double tempering treatment did not improve toughness conditions when variations in section size were considered. The table seems to indicate that there is a possibility of a slight improvement in the ductility by the employment of the double tempering treatment. Other studies also have indicated similar trends. However, considerably more testing would be necessary before definite trends could be positively identified. Such studies would require a careful check as to constant hardness conditions because the additional tempering treatment results in a longer heating time which, in turn, produces a lower hardness value. It has been observed that at a constant hardness there

TABLE 43

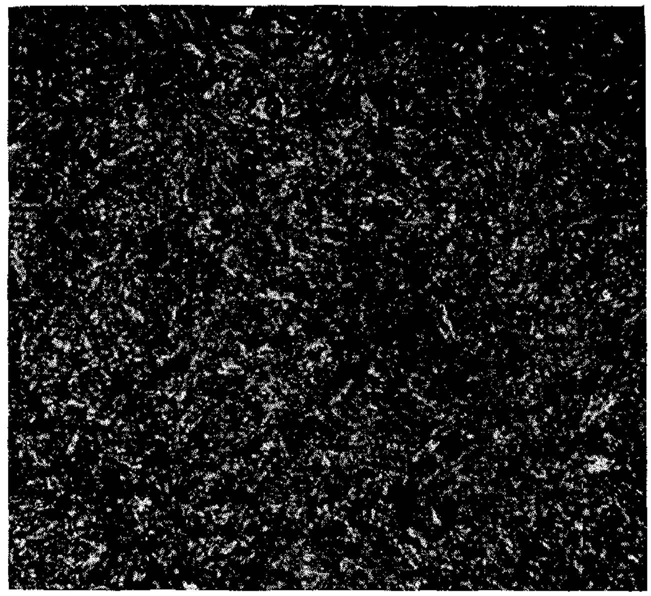
The Effect of Double Tempering on Mn-B and Mn-Cr-Mo Cast Steels

HEAT TREATMENT: Homogenize—1750°F for 15 minutes
Harden—1550°F for 30 minutes and water quench
Temper—Mn-B; 1200°F, 30 minutes, repeat once
Mn-Cr-Mo 1125°F, 30 minutes, repeat once

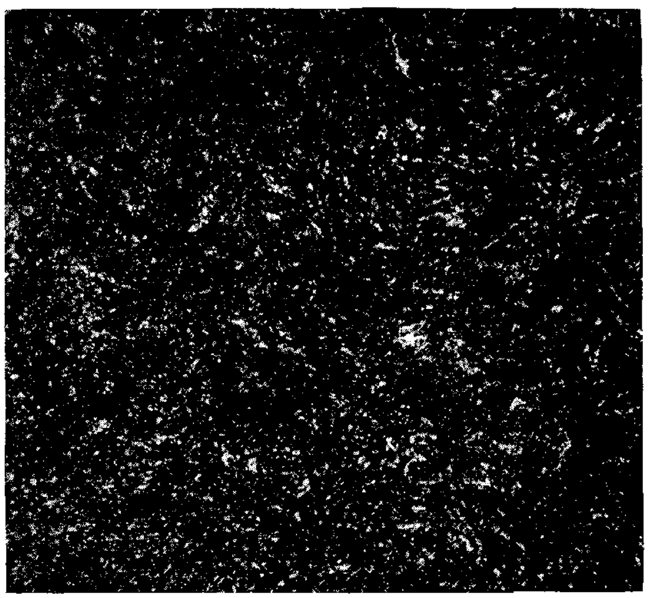
Tempering Treatment	Steel Type	Section Thick. inch	BHN	Charpy V-Notch Impact, ft. lbs. +70°F	–40°F	–80°F	Tensile Strength 1000 psi	Yield Point 1000 psi	Elon. %	R. A. %
Single	Mn-B	1	223	42	31	—	108.0	98.0	21.0	45.1
Double	Mn-B	1	215	43	31	—	106.0	97.0	21.5	39.7
Single	Mn-B	3	212	53	26	—	95.0	72.0	23.0	36.0
Double	Mn-B	3	197	50	21	—	104.5	89.0	25.0	56.8
Single	Mn-Cr-Mo	1	302	44	42	41	144.0	135.2	11.5	25.8
Double	Mn-Cr-Mo	1	305	42	40	34	141.7	133.0	9.0	18.7
Single	Mn-Cr-Mo	3	272	54	32	28	137.0	120.0	11.0	24.0
Double	Mn-Cr-Mo	3	269	54	37	28	131.7	118.3	9.5	17.0



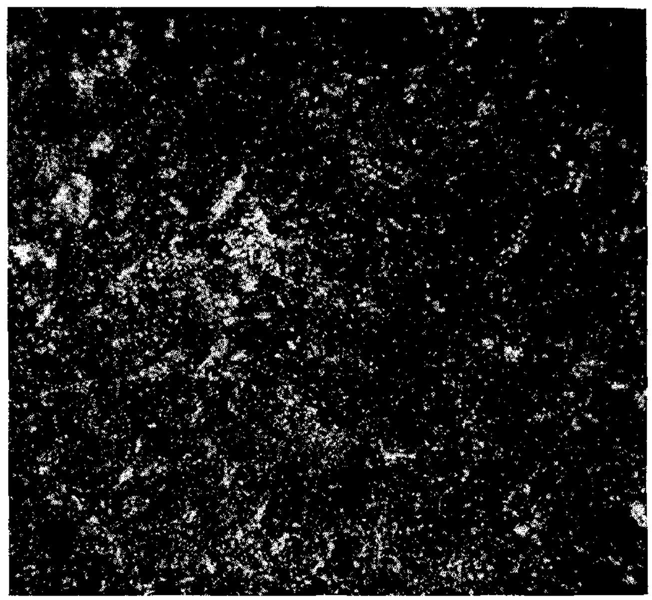
a. Single Temper. 1-inch section



b. Double Temper. 1-inch section

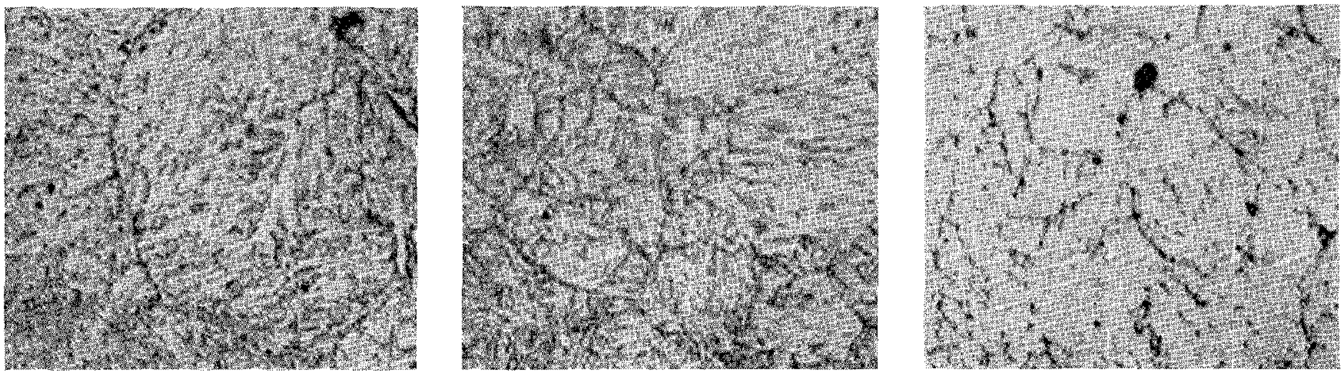


c. Single Temper. 3-inch section



d. Double Temper. 3-inch section

Figure 84—Comparison of the microstructure of single and double tempered Mn-Cr-Mo cast steels. Prior treatment: homogenized 1750 degrees F for 15 minutes, 1550 degrees F for 30 minutes. Water quenched and tempered 1125 degrees F for 30 minutes, water quenched. Double tempered treatment consisted of an additional temper at 1125 degrees F for 30 minutes. Water quenched. 500X. Nital etch

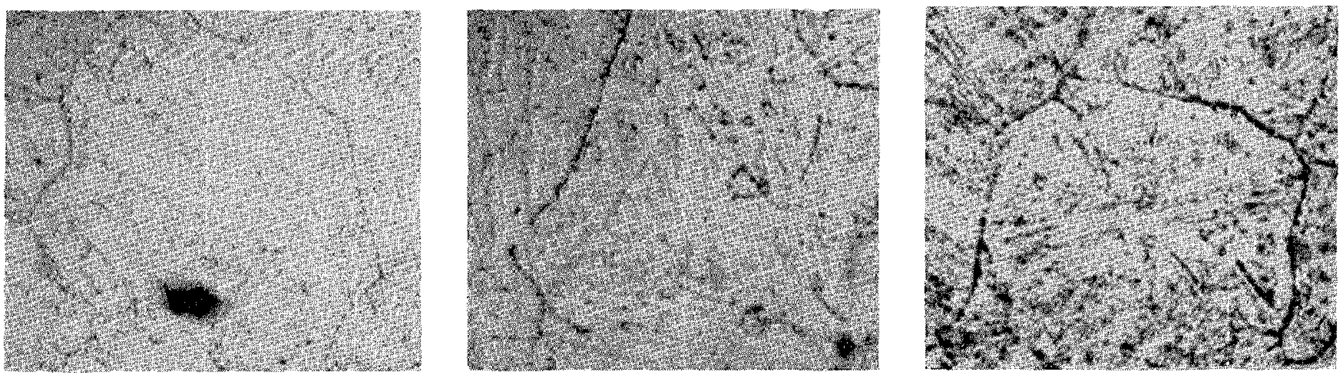


a. *1-inch section. Double tempered 1250°F 30 minutes*

b. *3-inch section. Double tempered 1250°F 30 minutes*

c. *6-inch section. Double tempered 1250°F 30 minutes*

Figure 85—Double temper, Cr-Mo cast steel. Zephiran chloride etch. The etch has been partially removed to make the grain boundaries more pronounced. 1000X. All steels homogenized at 1650 degrees F for 15 minutes, air cooled. Austenitized 1650 degrees F 15 minutes, water quenched



a. *1-inch section. Double tempered 1250°F 90 minutes*

b. *3-inch section. Double tempered 1250°F 90 minutes*

c. *6-inch section. Double tempered 1250°F 30 minutes*

Figure 86—Double temper, Mn-Ni-Cr-Mo cast steel. Zephiran chloride etch. Etch partially removed. 1000X. All steels homogenized at 1750 degrees F for 60 minutes, air cooled. Austenitized 1750 degrees F for 15 minutes, water quenched.

TABLE 44

The Effect of Double Tempering on Cr-Mo and Mn-Ni-Cr-Mo Cast Steels

HEAT TREATMENT:

Cr-Mo
- Homogenize—1650°F for 15 minutes, air cool
- Harden—1650°F for 15 minutes, water quench
- Temper—1250°F for 30 minutes, water quench, repeat

Mn-Ni-Cr-Mo
- Homogenize—1750°F for 60 minutes, air cool
- Harden—1750°F for 15 minutes, water quench
- Temper—1250°F for 90 minutes, water quench, repeat

Tempering Treatment	Steel Type	Section Thick. inch	BHN	Charpy V-Notch Impact, ft. lbs. +70°F	-40°F	-80°F	Tensile Strength 1000 psi	Yield Point 1000 psi	Elon. %	R. A. %
Single	Cr-Mo	1	254	50	52	51	116.9	95.2	16.3	42.6
Double	Cr-Mo	1	253	57	54	47	118.3	98.1	15.5	47.4
Single	Cr-Mo	3	259	66	61	57	123.3	102.6	14.0	40.6
Double	Cr-Mo	3	255	58	53	47	124.8	104.0	11.5	25.9
Single	Cr-Mo	6	250	73	62	47	117.9	91.1	8.0	24.5
Double	Cr-Mo	6	260	61	55	45	117.0	89.4	15.5	45.9
Single	Mn-Ni-Cr-Mo	1	254	36	28	24	117.0	94.5	15.7	38.0
Double	Mn-Ni-Cr-Mo	1	245	36	27	15	114.8	96.0	18.2	40.8
Single	Mn-Ni-Cr-Mo	3	253	42	37	35	—	—	—	—
Double	Mn-Ni-Cr-Mo	3	247	47	40	27	114.0	95.5	18.8	48.8
Single	Mn-Ni-Cr-Mo	6	253	48	46	44	116.4	96.0	15.0	31.0
Double	Mn-Ni-Cr-Mo	6	255	46	44	43	117.2	96.3	15.3	34.6

was no improvement in tensile properties with increased heating time. Therefore, it is most logical to expect that there would be no improvement in tensile-ductility properties by employing a double tempering heat treatment.

It should be indicated, however, that a marked improvement in ductility could result from double tempering if the hardenability of a steel was such that substantial quantities of austenite are retained and the tempering temperature was in the embrittlement range of below 1050 degrees F. The tempering temperatures in these studies were above 1100 degrees F.

Photomicrographs of the Cr-Mo and Mn-Ni-Cr-Mo steels, after a double tempering treatment, are illustrated in Figures 85 and 86. These plates can be compared with those of Figures 73 and 75 which show structures after a single tempering treatment. It will be observed that they are of similar appearance. The double tempered series, however, is more deeply etched to bring out the grain boundary conditions more clearly. Grain size, type and distribution of grain boundary constituents are similar in both cases though more pronounced for the Mn-Ni-Cr-Mo cast steel.

Summary of the Effect of Double Tempering

A study of four water quenched low-alloy cast steels, after double tempering as compared to single tempering (tempering temperatures above 1100 degrees F), showed that the toughness of the steels was not improved by a double tempering treatment.

SECTION XI
HEAT TREATMENT STUDIES ON NORMALIZED CAST STEELS

Carbon Cast Steel

A series of heat treatment studies on carbon steel was undertaken by Steel Castings Institute of Canada to show the effect of varying the normalizing temperature and time on the tensile and impact properties.

The composition of the steel was:

	Percent		Percent
Carbon	0.30	Nickel	0.06
Manganese	0.82	Chromium	0.06
Silicon	0.49	Molybdenum	0.02
Sulfur	0.023	Aluminum	0.15
Phosphorus	0.022		

Specimens for study were taken from the 1-inch coupon and 3-inch block castings described in Section I.

The heat treatment consisted of (1) a single normalize at one temperature and one time (1650 degrees F 1 hr.); (2) a normalize treatment at three temperatures for three holding times followed by a single tempering treatment (1550, 1650, 1750 degrees F for 15, 45 and 120 minutes, tempering 1250 degrees F for 1 hr.); (3) a double normalizing at three temperatures for three different times followed by tempering, and (4) the double normalizing followed by tempering and aging. The aging treatment consisted of holding the machined test bars at 400 degrees F for 72 hours, cooling the bars to room temperature and then testing.

Table 45 presents a detailed chart of the tensile and Charpy V-notch impact properties for 1-inch sections and Table 46 gives values for 3-inch sections. These tables indicate that each of the normalizing treatments ranging over 1550, 1650 and 1750 degrees F for 15, 45 and 120 minutes are equally effective. The economical heat treatment, therefore, would be one of employing a low temperature and a short time of 1550 to 1650 degrees F and a time of 15 to 30 minutes at temperature.

Table 47 compares a single normalizing treatment with a double normalizing treatment. A tempering treatment was not employed. Properties obtained following an aging treatment are also compared.

It will be observed that in the normalized condition (without tempering) the steel possessed low ductility because of hydrogen embrittlement (see Section XII). Adequate ductility was restored by either tempering or aging of the one-inch section. A comparison of Tables 45 and 47 will show that tempering was as effective as aging in restoring the ductility. However, the test results of Table 46 illustrate that aging, in addition to tempering, is required for 3-inch sections to produce adequate ductility to meet minimum specifications for tensile ductility.

The aged results fairly represent the property values which would have been attained in the absence of initial hydrogen embrittlement. The effects of double normalizing and of varying the normalizing temperature and time can be assessed just as well by examining normalized and tempered properties as by examining as-normalized properties.

Hardness variations obtained by normalizing from 1550 to 1750 degrees F were negligible; there-

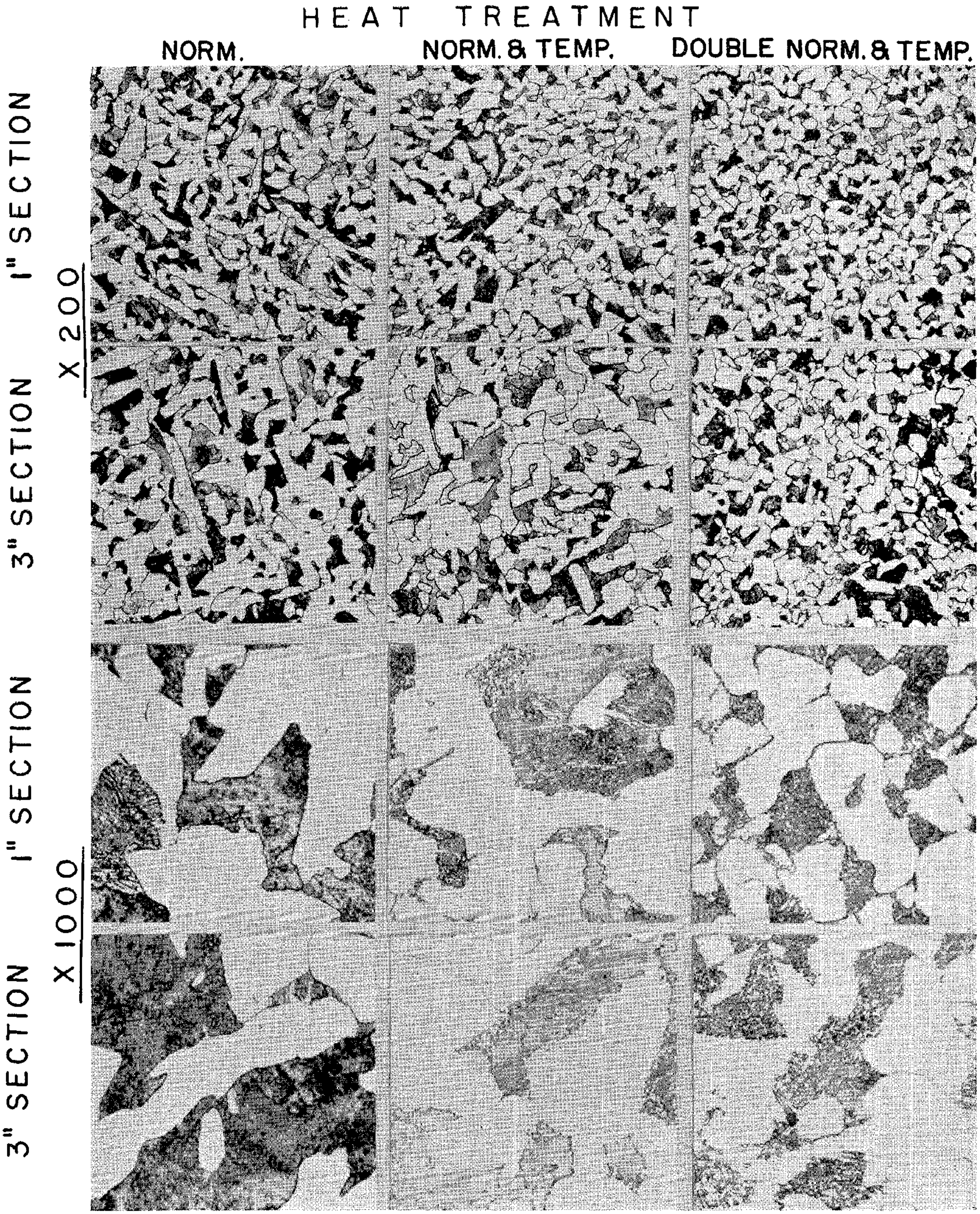


Figure 87—Normalized carbon cast steel. Comparison of microstructures from the center of one-inch and three-inch sections.
Left—single normalize, 1650°F - 30 minutes
Center—normalize, 1650°F - 30 minutes, and tempered, 1250°F - 60 minutes
Right—double normalize, both at 1650°F - 30 minutes, and tempered, 1250°F - 60 minutes

fore, only hardness values at 1650 degrees F are reported. Hardnesses were obtained on the tensile specimens by Rockwell B averaged and then converted to Brinell hardness numbers.

A series of photomicrographs is arranged in Figure 87 to illustrate that the three-inch section exhibits a coarser grain size than the one-inch section, and also to show that double normalizing produces a finer structure than single normalizing. Furthermore, a comparison of the untempered structure with the tempered structure can be made by studying Figure 87.

Studies on the normalizing of one-inch and three-inch sections of carbon cast steels have resulted in the following findings:

1—Single normalizing was just as effective as double normalizing for one-inch and three-inch sections in the tempered and aged condition.

2—The effect of different normalizing temperatures (1550, 1650 and 1750 degrees F) and holding times (15, 45 and 120 minutes) are minor.

3—One of the carbon steels of the study was embrittled by hydrogen to a small extent in the one-inch section and to a large extent in the three-inch section.

4—Tempering at 1250 degrees F for 1 hour eliminated the loss of ductility in one-inch sections but was ineffective on three-inch sections. Aging was necessary to produce adequate ductility in test bars from three-inch sections.

5—In the aged condition (considered to be the normal condition unaffected by hydrogen) the reduction of area and elongation are significantly higher and more consistent for the one-inch sections than for the three-inch sections.

Mn-B Cast Steel

An alloy cast steel of the low hardenability type, manganese-boron, was also studied in the normalized condition to ascertain the effect of normalizing temperature and heating time on the mechanical properties. This steel was investigated for two section thicknesses, 1 and 3 inch.

TABLE 45

Effect of Normalizing Temperature and Time on the Mechanical Properties of One-Inch Sections of Carbon Cast Steel

HEAT TREATMENTS: Prior Normalize—1650°F, 30 minutes, air cooled
Final Normalize—1550, 1650, 1750°F for 15, 45 and 120 minutes, air cooled
Temper—1250°F for 60 minutes, air cooled
Age—400°F for 72 hours, air cooled (finished test bar)

Mechanical Property	Normalizing Temp. °F	Time at Final Normalizing Temperature (minutes)								
		Single Normalize - Tempered			Double Normalize - Tempered			Double Normalize - Tempered, Aged		
		15	45	120	15	45	120	15	45	120
Tensile Strength (1000 p.s.i.)	1550	79.4	79.4	78.5	79.4	79.0	78.8	78.9	79.2	80.0
	1650	78.3	78.5	78.0	78.6	78.5	78.3	78.5	78.2	78.6
	1750	78.0	78.4	79.0	77.9	78.3	77.9	78.1	77.6	78.1
Yield Point (1000 p.s.i.)	1550	48.7	49.0	49.1	52.7	50.9	52.9	51.2	50.4	55.4
	1650	50.0	49.4	52.9	50.0	53.4	52.3	50.7	49.8	50.9
	1750	50.6	52.2	48.7	53.6	52.7	52.0	49.9	50.2	50.6
Elong. (%)	1550	29.5	29.5	31.0	30.2	30.2	32.5	31.0	28.5	30.5
	1650	30.0	30.2	31.0	32.5	31.5	31.5	32.2	31.0	31.7
	1750	31.0	30.5	30.0	31.7	30.7	30.2	31.7	32.0	32.2
R.A. (%)	1550	55.7	56.0	54.2	56.2	52.1	56.4	56.0	51.6	56.4
	1650	54.8	56.3	55.5	57.0	55.2	57.0	55.5	53.8	57.3
	1750	53.2	52.2	55.8	55.2	57.2	56.1	55.3	58.8	56.8
Charpy V-Notch at +70°F (ft-lbs)	1550	35	44	39	43	43	43	41	43	39
	1650	35	36	33	41	40	39	47	55	48
	1750	36	37	34	38	38	38	45	47	43
Charpy V-Notch at −40°F (ft-lbs)	1550	13	17	16	18	17	16	16	15	14
	1650	13	14	13	17	16	12	15	13	13
	1750	14	14	13	12	15	14	14	12	15
BHN	1650	155	155	154	156	155	154	155	153	153

TABLE 46

Effect of Normalizing Temperature and Time on the Mechanical Properties of Three-Inch Sections of Carbon Cast Steel

HEAT TREATMENTS: Prior Normalize—1650°F, 30 minutes, air cooled
Final Normalize—1550, 1650, 1750°F for 15, 45 and 120 minutes, air cooled
Temper—1250°F for 60 minutes, air cooled
Age—400°F for 72 hours, air cooled (finished test bar)

Mechanical Property	Normalizing Temp. °F	Time at Final Normalizing Temperature (minutes): Single Normalize - Tempered, Aged 15	Single Normalize - Tempered, Aged 45	Single Normalize - Tempered, Aged 120	Double Normalize - Tempered, Aged 15	Double Normalize - Tempered, Aged 45	Double Normalize - Tempered, Aged 120	Double Normalize - Tempered 15	Double Normalize - Tempered 45	Double Normalize - Tempered 120
Tensile Strength	1550	77.1	77.5	76.7	77.1	77.0	77.0	74.5	75.2	76.6
(1000 p.s.i.)	1650	76.9	77.0	76.5	76.4	76.6	76.8	75.4	—	75.6
	1750	76.2	76.7	76.8	76.4	76.5	76.9	76.0	75.2	76.0
Yield Point	1550	44.9	43.9	44.0	47.4	47.8	49.0	45.4	47.5	49.0
(1000 p.s.i.)	1650	44.8	48.4	46.2	49.0	50.6	50.2	50.2	—	49.3
	1750	43.1	46.6	46.0	48.4	46.4	50.0	47.1	47.0	46.8
Elong. (%)	1550	26.0	25.7	26.0	24.2	24.7	30.0	16.0	17.0	20.0
	1650	28.7	27.0	28.2	25.5	31.0	25.5	16.5	—	16.7
	1750	29.2	28.0	29.5	30.7	28.0	28.5	18.7	16.5	19.5
R.A. (%)	1550	41.4	38.5	35.6	38.5	34.1	44.5	20.8	27.1	25.6
	1650	45.6	42.1	42.2	36.9	46.7	33.2	24.5	—	23.1
	1750	40.0	39.8	43.9	44.7	43.4	42.2	27.5	23.7	28.2
Charpy V-Notch	1550	34	33	34	42	39	43	37	37	38
at +70°F (ft-lbs)	1650	33	35	36	41	44	39	34	34	32
	1750	36	37	34	44	43	41	34	31	33
Charpy V-Notch	1550	7	7	5	11	9	8	10	9	8
at −40°F (ft-lbs)	1650	8	9	8	10	10	12	11	12	9
	1750	7	7	7	9	10	10	9	9	10
BHN	1650	151	151	151	151	150	148	150	152	150

TABLE 47

CARBON CAST STEEL

Comparative Examples of Mechanical Properties in the Normalized Condition (No Tempering), With and Without Aging, for One-Inch and Three-Inch Sections

HEAT TREATMENTS: Normalize—1650°F, 1 hour, air cooled - no tempering
Age—400°F for 72 hours (finished test bars)

Mechanical Property	Section Size Inch	Condition: Not Aged, Single Normalize	Not Aged, Double Normalize	Aged, Single Normalize	Aged, Double Normalize
Tensile Strength	1	83.3	83.5	83.3	83.2
(1000 p.s.i.)	3	78.6	—	80.5	80.1
Yield Point	1	52.2	56.8	49.5	56.2
(1000 p.s.i.)	3	49.6	—	48.5	50.7
Yield: Tensile Ratio	1	0.627	0.68	0.594	0.675
	3	0.631	—	—	0.633
Elong. (%)	1	23.5	24.5	28.0	30.0
	3	14.2	—	25.2	21.2
R.A. (%)	1	31.9	35.2	52.4	51.4
	3	20.6	—	34.2	32.1
Charpy V-Notch	1	38	49	47	58
at +70°F (ft-lbs)	3	37	—	41	49
Charpy V-Notch	1	13	17	12	13
at −40°F (ft-lbs)	3	9	—	9	13

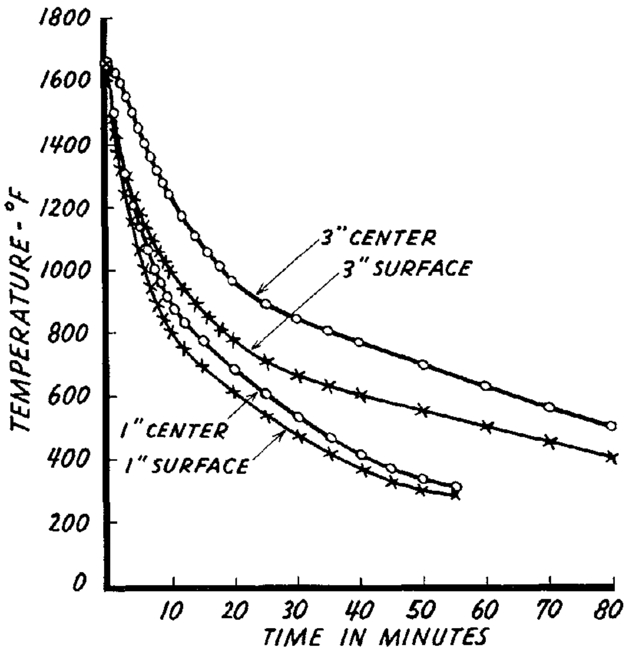


Figure 88—Cooling curve for 1- and 3-inch sections, normalizing (cooling in air) from 1650 degrees F

The composition of the steel was:

	Percent
Carbon	0.30
Manganese	1.51
Silicon	0.38
Sulfur	0.049
Phosphorus	0.037
Boron	0.0045 added

The heat treatment consisted of employing a homogenization treatment in one case and no prior treatment in the other. The homogenization treatment, strictly speaking, was a normalizing treatment at 1850 degrees F for 15 minutes and air cooled. The high temperature was chosen because it was thought that this would produce the most drastic change in conditions, if any. Previous work showed no advantage in going to any longer holding time than 15 minutes.

The cooling curves for the 1- and 3-inch sections for surface and center location thermocouples are shown in Figure 88. At 1000 degrees F a gradient of 60 degrees F is observed in the 1-inch thick section and a 240 degree F gradient exists for the 3-inch section.

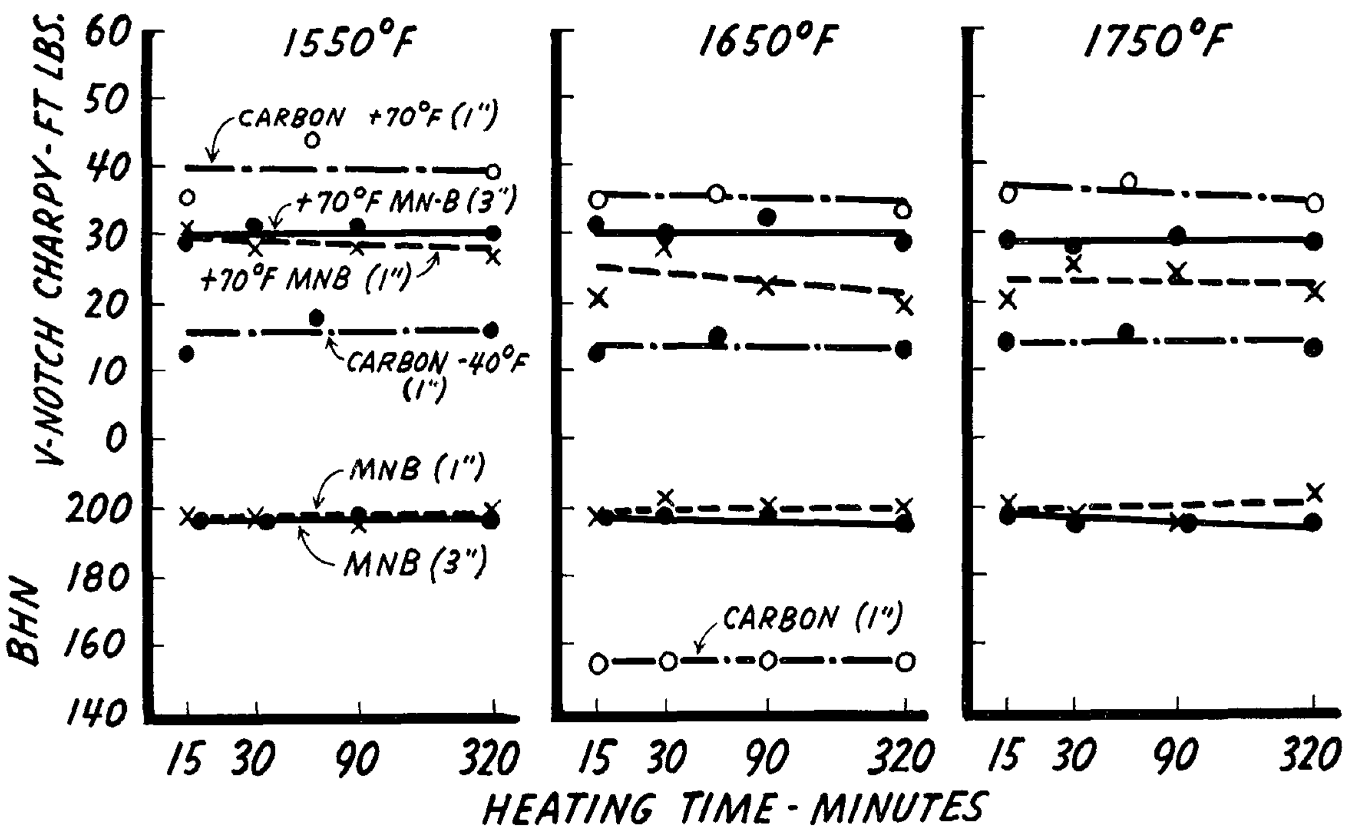


Figure 89—Carbon and Mn-B cast steel normalized; showing that heating temperature or length of heating time has no effect on the Charpy V-notch impact properties.

The mechanical property values are given in Tables 48 and 49. The 1-inch section values are summarized in Table 48. It will be observed immediately that the prior homogenization heat treatment had no effect on the toughness or the tensile test values. Hardness values were constant within a narrow range. Also, values at low temperatures for short times were equal to those of high temperatures for long times, such as 1550 for 15 minutes as compared to 1750 for 120 minutes.

The 3-inch section values presented in Table 49 are, in general, similar to those of the one-inch section. There are, however, some differences which are pointed out as follows: The group with the prior homogenization treatment was of lower hardness by 5 to 6 points Brinell and the +70 degree impact value was increased by about 4 ft-lbs.; also, the ductility values are slightly higher by 2 to 4 percent. *This may be only the normal shift that goes along* with the decrease in hardness values, or the prior homogenization may be reflected along with the slight hardness drop.

The Mn-B cast steel is compared with the carbon cast steel in Figure 89. The carbon steel is heat treated to a lower hardness level of 155 BHN. It will be observed, however, that all trend lines are horizontal across the graph.

The microstructure of the Mn-B normalized steel is illustrated in Figure 90. It will be observed that a finer grain size was secured by employing the prior homogenizing heat treatment.

Summary of Normalizing of Cast Steel

Studies on the normalizing of one- and three-inch sections of carbon and manganese-boron cast steels have proved the following:

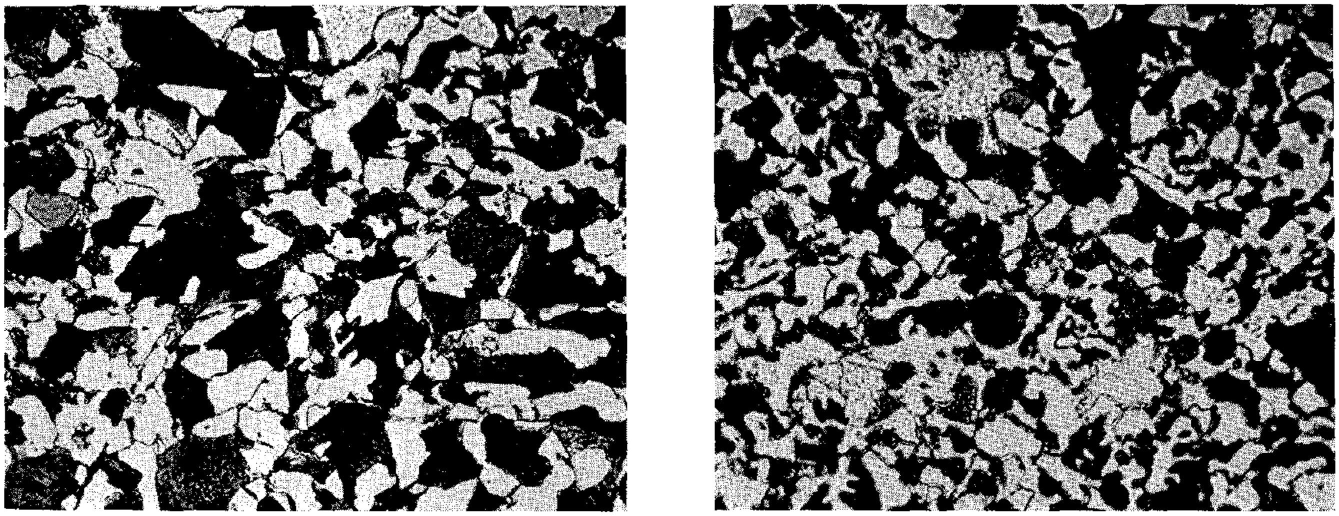
1—Single normalizing produces toughness and tensile properties of the same order as double normalizing for 1- and 3-inch sections of carbon and manganese-boron cast steels.

2—The effect of different normalizing temperatures and holding times is of very minor importance in securing most acceptable mechanical properties.

TABLE 48
Mn-B Cast Steel. 1-inch Section
Effect of Normalizing Temperature and Time on the Mechanical Properties

Homo-genize	Normalize† Temp. °F	Normalize† Time min.	BHN	V-notch Impact ft. lbs. +70°F	V-notch Impact ft. lbs. −40°F	Tensile Strength 1000 psi	Yield Point 1000 psi	Elon. in 2 in %	Red. of Area %
None	1550	15	197	30	9	99.5	65.5	24	43.3
		30	197	28	5	98.5	64.5	25	45.9
		60	195	28	6	98.5	67.0	24	42.7
		120	198	27	5	98.5	64.5	25	43.3
None	1650	15	197	20	3	99.0	63.5	24	47.4
		30	202	28	4	99.0	65.0	24	46.5
		60	200	22	5	99.0	64.5	23	40.0
		120	198	19	5	100.0	64.0	23	40.3
None	1750	15	200	20	4	100.0	66.5	23	44.2
		30	197	25	4	98.0	63.0	23	46.2
		60	195	24	5	97.5	67.0	22	42.7
		120	204	21	5	100.0	67.0	21	40.0
1850°F 15 min.	1550	15	200	32	7	98.5	67.5	24	46.2
		30	198	26	8	97.5	66.0	23	33.7
		60	197	30	6	98.0	62.5	23	40.6
		120	197	23	4	97.5	64.5	24	44.2
1850°F 15 min.	1650	15	192	24	3	99.0	65.0	24	47.2
		30	197	24	6	98.5	64.0	24	45.9
		60	197	24	5	100.0	66.0	24	44.2
		120	196	26	5	99.0	66.0	22	40.3
1850°F 15 min.	1750	15	198	25	4	98.0	63.5	23	41.2
		30	194	23	5	98.0	63.5	24	44.8
		60	197	19	3	99.0	64.5	23	43.9
		120	195	20	4	99.5	68.0	21	37.2

† No tempering after normalizing



a. 1-inch Section. No Homogenization, normalize at 1650°F 30 minutes; no temper

b. 3-inch Section. Homogenize 1850°F for 15 minutes; normalize 1650°F for 30 minutes; no temper

Figure 90—Mn-B cast steel. Nital etch. 500X

TABLE 49

Mn-B Cast Steel. 3-inch Sections
Effect of Normalizing Temperature and Time on the Mechanical Properties

Homogenize	Normalize† Temp. °F	Normalize† Time min.	BHN	V-notch Impact ft. lbs. +70°F	V-notch Impact ft. lbs. −40°F	Tensile Strength 1000 psi	Yield Point 1000 psi	Elon. in 2 in %	Red. of Area %
None	1550	15	197	29	8	96.5	65.5	22	34.0
		30	197	31	7	97.5	66.0	22	31.7
		60	198	31	6	96.5	66.5	23	40.6
		120	197	30	11	96.0	67.5	23	39.0
None	1650	15	197	31	8	98.0	66.5	22	36.2
		30	197	30	9	96.5	65.0	24	40.9
		60	197	32	9	96.0	67.0	23	40.3
		120	195	28	7	96.0	67.0	24	33.7
None	1750	15	197	29	7	96.0	69.5	23	39.0
		30	195	28	8	96.0	67.5	23	37.2
		60	195	29	7	95.0	68.5	21	33.3
		120	195	28	9	95.5	67.0	24	38.7
1850°F 15 min.	1550	15	189	38	14	96.0	63.0	26	46.2
		30	189	39	13	95.5	65.0	23	40.9
		60	192	37	13	96.0	68.0	25	43.9
		120	194	35	7	96.5	66.5	22	33.7
	1650	15	194	41	11	96.5	69.5	26	48.8
		30	194	33	13	95.5	65.5	25	39.0
		60	190	30	5	96.0	63.5	24	39.3
		120	189	30	6	95.5	67.0	24	44.8
	1750	15	192	30	13	95.0	62.5	23	36.2
		30	194	32	10	95.0	67.5	24	38.7
		60	194	31	5	96.0	64.5	26	46.2
		120	190	33	8	95.5	64.0	23	39.0

† No tempering after normalizing

3—Test results indicate that for economic purpose, time saving and development of maximum properties attainable through normalizing heat treatment, the following procedures should apply:

(a) do not employ a prior homogenizing (normalizing) heat treatment;

(b) heat castings to the normalizing temperature as quickly as possible;

(c) obtain by heat transfer studies the time it takes various casting sections to come to temperature;

(d) heat castings for only a short time (15 to 30 minutes totally) after they have reached the normalizing temperature. Holding time does not vary according to section thickness;

(e) employ a low normalizing temperature, 50 to 100 degrees F above the critical temperature;

(f) air cool as rapidly as possible.

SECTION XII

EFFECT OF AGING ON THE TOUGHNESS OF CAST STEELS

The presence of hydrogen in solid steel is responsible for low ductility values when the steel is tension tested after heat treatment. A definite improvement can be obtained, which may be considerable in some cases, by heating the steel at low temperatures for various periods of time depending upon the section thickness of the steel. This low temperature heating is referred to as *aging*.

Aging takes place at room temperature as well as at 400 or 600 degrees F; however, the time of aging to arrive at low hydrogen contents may take months or even years for heavy section thicknesses. However, the process of aging can be speeded up by employing a temperature of 400 degrees F. For example, it may take several months to age a one-inch section at 70 degrees, whereas the same improvement could be obtained by heating at 400 degrees F for 24 hours.

The aging time can be further reduced by heating at 1000 or 1200 degrees F. In fact, tempering is, in a manner of speaking, an aging operation as well. The drawback of using high aging temperatures is that the final hydrogen content of the steel is at a much higher level than obtainable at low aging temperatures. In fact, it may be at such a high level that there would be little, if any, improvement in the ductility properties.

Aging at 70 degrees produces the lowest hydrogen content in the steel, but the aging time is too long for test purposes. Therefore, a compromise is made to employ temperatures below the blue brittle range (600 to 900 degrees F for most steels). Aging temperatures of about 400 degrees F are usually selected for test purposes.

Aging has, in some cases, improved the toughness of cast steels as well as the ductility; but only if the steel contains in the solid state hydrogen contents of upwards of 2 parts per million. If the hydrogen content is around ½ part per million or below, aging will not result in ductility or toughness improvement.[4]

The studies of this section were carried out with the idea of learning whether the steels used in these research studies would show improved toughness and ductility properties. The studies were not an extensive study on aging nor were they meant to be such a study. If the steels did not show improvement on aging, they could be considered as having low hydrogen contents in the solid state.

Carbon Cast Steel

The effect of aging on the mechanical properties of carbon cast steel was obtained by studying 1-inch sections of normalized, water quenched and tempered steel and also by studying one- and three-inch sections of normalized and tempered steel.

Table 50 shows that aging at 400 degrees F for up to 240 hours has no observable effect on the tensile and impact properties of normalized, water quenched and tempered properties of the carbon cast steel of heat No. 1. This heat was not embrittled by hydrogen. However, aging of heat No. 2 carbon steel greatly increased the ductility and toughness as may be observed by referring back to Tables 46 and 47 in Section XI.

Aging improved impact and ductility properties for one steel and not for the other. This indicates that steelmaking methods are very important.

Mn-Cr-Mo Cast Steel

The Mn-Cr-Mo cast steel was aged in one- and three-inch thick sections following a homogenizing, quench and temper treatment. The aging temperature was 400 degrees F. Results of the aging studies are given in Table 51. Aging times should be considered on the basis of the machined impact bar and tensile bar. These bars were machined, then aged and tested. Sixty minutes for a 0.505 in diameter test specimen are equivalent to about 48 hours for a 1-inch thick plate section.

TABLE 50
Effect of Aging on the Mechanical Properties of One-inch Sections

HEAT TREATMENT: Normalize—1650°F, 30 minutes, air cool
Harden—1600°F, 30 minutes, water quench
Temper—1150°F, 30 minutes, air cool
Age—400°F for 0, 15, 30, 60, 120 and 240 hours

Mechanical Property	Aging time at 400°F (hours) 0	15	30	60	120	240
T. S. (1000 psi)	95.1	93.8	93.3	95.3	94.0	95.1
Yield (1000 psi)	69.3	70.2	68.6	73.2	67.6	73.4
Elongation (%)	25.8	27.5	27.0	25.2	24.5	25.0
R. A. (%)	56.0	57.7	57.1	54.3	47.8	58.5
Charpy V-Notch at +70°F (ft-lbs)	53	55	59	56	56	53
Charpy V-Notch at −40°F (ft-lbs)	34	29	28	30	33	31

It will be observed from Table 51 that if there was any improvement in the toughness or ductility properties on aging, it certainly can be considered as very minor.

Cr-Mo Cast Steel and Mn-Ni-Cr-Mo Cast Steel

Aging studies were carried on for the Cr-Mo and Mn-Ni-Cr-Mo cast steels in 1-, 3- and 6-inch sections after the steel had been homogenized, quenched and tempered. The results are reported in Tables 52 and 53.

The 1-inch and 3-inch section Cr-Mo steel showed no change in impact or ductility on aging. The impact results for the 6-inch section were very mixed and told nothing. However, aging possibly improved the ductility of the 6-inch section.

TABLE 51
Effect of Aging Mn-Cr-Mo Cast Steel in 1- and 3-inch Sections

HEAT TREATMENT: Homogenize—(1) 1850°F for 15 minutes;
(2) 1750°F for 30 minutes
Harden—(1) 1550° for 30 minutes;
(2) 1550°F for 15 minutes. Water quenched
Temper—(1) 1200°F for 30 minutes;
(2) 1125°F for 30 minutes. Water quenched
Aging—400°F for various times

Homogenize °F	Harden °F	Temper °F	Aging Time Min.	BHN	Charpy V-Notch Impact, ft. lbs. +70°F	−40°F	−80°F	Tensile 1000 psi	Yield 1000 psi	Elon. in 2" %	Red. of area %
					1-inch Section						
1850	1550	1200									
15 min	30 min	30 min	none	223	35	31	—	113.0	104.0	21	45
15 min	30 min	30 min	60	217	39	30	—	109.5	99.5	21	40
			240	229	38	31	—	112.0	98.0	20	42
15 min	30 min	30 min	480	223	38	30	—	109.0	99.5	19	41
			240[a]	217	39	30	—	110.0	98.0	21	41
1750	1550	1125									
30 min	15 min	30 min	none	311	40	38	17	144.5	134.0	10	23
30 min	15 min	30 min	60	311	44	39	20	141.5	131.0	10	26
			240	321	42	30	—	—	—	—	—
30 min	15 min	30 min	480	321	40	30	—	—	—	—	—
			60[b]	300	49	45	18	138.0	125.5	10	26
					3-inch Section						
1850	1550	1200									
15 min	30 min	30 min	none	194	50	22	—	104.0	85.0	20	48
15 min	30 min	30 min	240	198	50	20	—	104.5	85.5	20	51
1750	1550	1150									
30 min	15 min	30 min	none	255	50	21	17	128.8	112.0	10	19
30 min	15 min	30 min	240	260	47	19	14	127.0	112.5	9	19

[a] Retemper following aging 1200 degrees F for 30 minutes.
[b] Retemper following aging 1125 degrees F for 30 minutes.

TABLE 52

Effect of Aging Cr-Mo Cast Steel in 1-, 3- and 6-inch Sections

HEAT TREATMENT: Homogenize
Harden—1650°F for 30 minutes
Temper—1250°F for 30 minutes
Aging—400°F for 1, 4 and 8 hours

Section Thickness Inches	Aging Time Hrs.	BHN	Charpy V-Notch Impact, ft. lbs. +70°F	−40°F	−80°F	BHN	Tensile 1000 psi	Yield 1000 psi	Elong. %	Red. of Area %
1	none	258	65	59	47	269	124.4	99.3	18.5	50.4
	1	264	69	60	52	269	121.5	99.6	17.0	49.3
1	4	264	61	61	44	269	124.5	99.2	16.2	46.2
	8	261	65	60	51	269	124.0	105.0	16.5	41.8
1	8*	244	78	69	48	255	117.0	96.7	18.5	51.0
3	none	279	52	52	44	277	124.8	101.2	11.5	27.6
	1	279	51	50	42	269	124.8	97.8	11.5	28.8
3	4	277	49	47	37	277	127.0	101.2	11.3	24.6
	8	279	53	48	31	277	129.9	104.8	10.5	29.5
3	8*	269	54	52	45	255	120.1	99.0	16.5	33.2
6	none	238	82	80	67	228	107.2	82.7	19.0	48.6
	1	235	71	65	57	231	106.5	86.3	19.0	50.7
6	4	235	73	70	56	228	108.2	86.6	18.5	55.4
	8	245	87	75	79	228	106.1	84.8	20.3	53.1
6	8*	218	89	87	53	228	105.4	82.6	21.5	56.7

* Retemper following aging 1250 degrees F for 30 minutes.

TABLE 53

Effect of Aging Mn-Ni-Cr-Mo Cast Steel in 1-, 3- and 6-inch Sections

HEAT TREATMENT: Homogenize
Harden—1650°F for 30 minutes
Temper—1250°F for 30 minutes
Aging—400°F for 1, 4 and 8 hours

Section Thickness Inches	Aging Time Hrs.	BHN	Charpy V-Notch Impact, ft. lbs. +70°F	−40°F	−80°F	BHN	Tensile 1000 psi	Yield 1000 psi	Elong. %	Red. of Area %
1	none	264	24	12	11	274	125.8	106.7	13.0	31.8
	1	261	25	15	11	286	125.7	106.5	13.0	34.8
1	4	260	34	25	16	277	125.6	107.7	14.3	38.2
	8	262	35	26	16	278	125.2	106.5	14.8	35.5
1	8*	254	37	32	21	262	120.3	102.0	13.8	38.4
3	none	276	27	18	15	293	128.8	113.7	5.0	13.8
	1	280	30	16	14	293	133.3	113.7	7.0	—
3	4	271	31	17	13	293	133.1	111.6	6.0	12.3
	8	282	29	16	14	293	136.7	111.2	12.0	20.7
3	8*	252	45	43	35	—	—	—	—	—
6	none	280	51	41	29	277	123.6	100.5	13.5	24.1
	1	254	53	50	50	277	120.5	96.6	16.0	38.0
6	4	258	58	54	49	277	123.4	101.3	14.5	35.1
	8	283	34	29	20	286	123.7	106.1	11.0	23.8
6	8*	253	61	42	30	269	114.9	86.0	14.0	26.5

* Retemper following aging 1250 degrees F for 30 minutes.

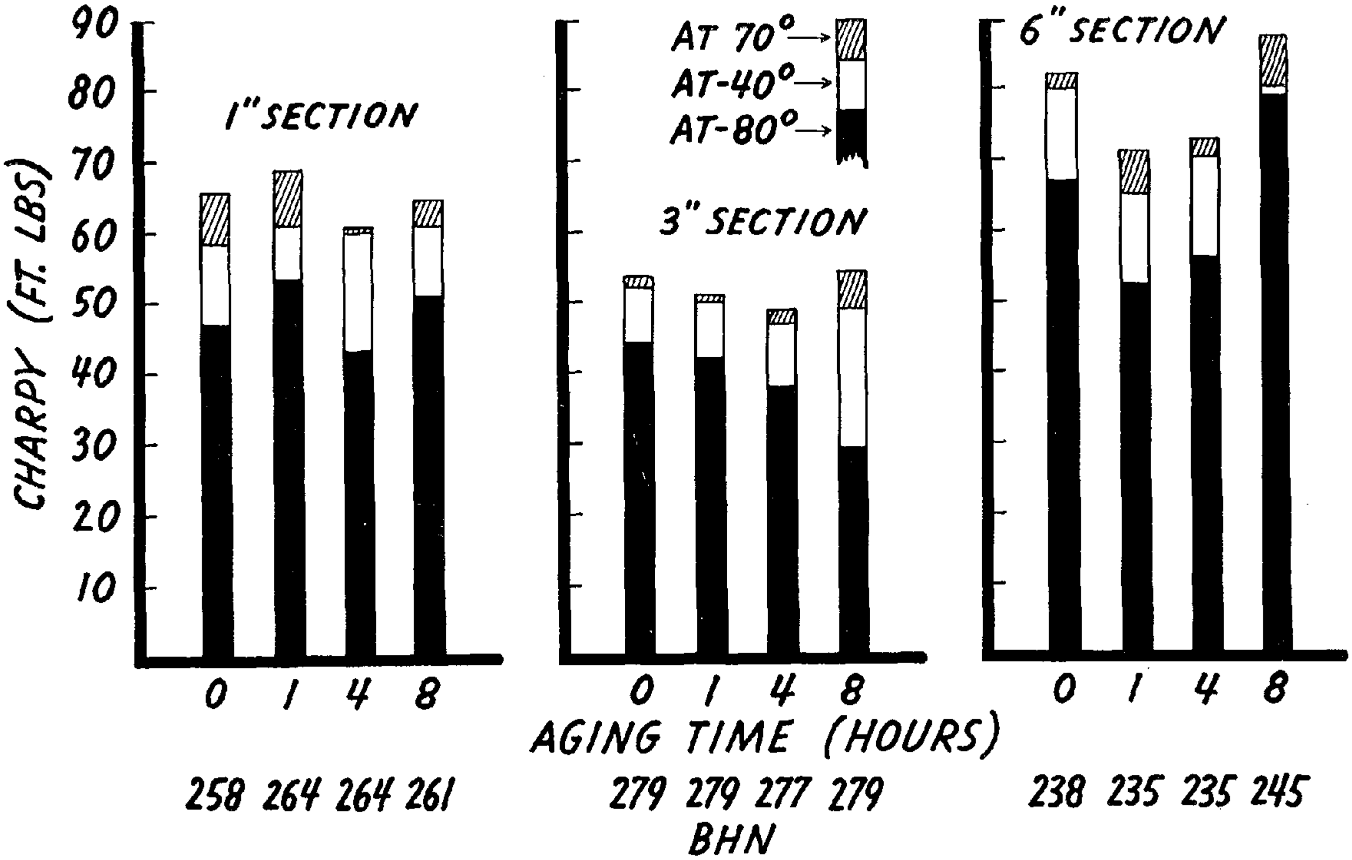


Figure 91—Effect of aging at 400 degrees F on homogenized, quenched and tempered Cr-Mo cast steel. Charpy V-notch impact properties for various section thicknesses are compared

Impact values obtained for 1-, 3- and 6-inch sections at various aging times at 400 degrees F are shown in Figure 91 for the Cr-Mo cast steel. It will be observed that there is no pronounced effect of impact improvement resulting from the aging treatment.

Table 53 for the Mn-Ni-Cr-Mo steel shows that both toughness and ductility are improved by the employment of the aging treatment, at least for the 1-inch thick sections. Improvement was slight but after 8 hours of aging there was some improvement. The data for the 6-inch section were rather confusing because of the unreasonably low values for the 8-hour aging. Again, all aging was performed on 0.505-inch test bars and impact bars after they had been removed from the 1-, 3- and 6-inch sections.

Summary of the Effect of Aging

Some properly heat treated cast steels show an improvement in toughness and ductility by employing an aging treatment at 400 degrees F. This treatment may or may not be necessary depending on the steelmaking process. Aging is not necessarily a requirement in high quality, short time heat treatment of steel castings.

SECTION XIII

THE RATE OF HEATING AND DELAYED QUENCHING OF STEEL CASTINGS

Most heat treatment procedures and many specifications for steel castings admonish the operator to heat the castings slowly and uniformly. This rule-of-thumb has become so ingrained within the industry that to do otherwise is looked upon as a very dangerous and unwise procedure resulting in warped and cracked castings.

However, it has been previously known and again shown in the sections of this report that excessive temperature gradients are not possible even under conditions of drastic heating, such as putting various sections of cast steel at room temperature into furnaces at 1850 degrees F.

Most operators will concede that it is possible to place simple shaped castings, such as plates, blocks, cylinders, etc., in hot furnaces and heat them quickly into the heat treating temperature without the castings cracking or distorting. However, the same operators definitely go on record as stating that complex shaped castings of variable section thicknesses would crack if given this drastic treatment.

Also, it has been repeatedly stated that the composition of the steel is likewise critical in determining the rate of heating. It has been stated that the alloy steels must be heated more slowly than the carbon steels and that high-carbon steels require slower heating than low-carbon steels.

The cast steels of concern in this study cover most all the carbon and low-alloy cast steels with carbon contents from 0.15 to 0.45 percent and alloy content ranging upward to a total of 8 percent. If these steels are to be employed in short-time heat treatment, it is most advisable that time be saved during the heating cycle. The maximum time, of course, can be saved by placing the cold castings into austenitizing and tempering furnaces with these furnaces maintained at the selected heat treating temperatures.

The plans for research to prove the acceptability of fast heating cycles were to secure castings which supposedly would crack on fast heating. All members of the Technical Research Committee as well as all members of the Ordnance Metallurgical Advisory Committee on Cast Armor, and the Technical and Operating Groups of Steel Founders' Society were asked to suggest casting designs.

It was interesting to observe that with all the publicity given to this phase of the research, there were very few suggestions put forward of castings which cracked upon heating. A few castings were suggested which cracked upon quenching, but it was soon determined that this was a manifestation of the well-known quench cracking. It has been well substantiated that complex design castings of widely varying cross section may crack during quenching, especially if the castings are permitted to stay in the water until the castings are cold.

Over a year was given to seeking a casting design which would crack by varying the heating rates. Finally, three castings were suggested which produced cracking when heated other than very slowly and uniformly. These castings were: (1) an I-beam design with risers in place during heat treatment; (2) a trailing idler arm, and (3) a streetcar wheel.

I-Beam Casting

A sketch of the I-beam casting is illustrated in Figure 92. This sketch shows the dimensions of the casting, the thickness of the sections, and the dimensions and location of the gates and risers.

The casting was produced in a 4-way alloy steel of 9530 grade. This steel is of high hardenability and, therefore, would be more liable to crack on heating than a carbon steel casting of the same design.

The casting was of the following composition:

	Percent
Carbon	0.32
Manganese	1.41
Chromium	0.59
Nickel	0.30
Molybdenum	0.57
Phosphorus	0.012
Sulfur	0.011
Silicon	0.38

The casting was produced in green sand and following cleaning it was examined 100 percent by magnetic particle testing. The casting was relatively free from surface imperfections. A few small checks were removed by grinding and blending to the surface contour. There were no surface defects at the time that the casting was placed in the heat treating furnace.

The furnace was held at a temperature of 1750 degrees F and the 75 degree F casting was placed into the furnace and permitted to heat as rapidly as possible. It took about 45 minutes for the casting to come to temperature at the heaviest section (the riser) and after 15 minutes of heating, the casting was removed from the furnace and air cooled. Very little scale had formed in this short-time heat treatment. The casting was cleaned and magnetic particle tested and not one discontinuity could be found.

Trailing Idler Arm

It was thought that perhaps the I-beam casting was not sufficiently complicated and that the section thicknesses did not vary sufficiently. Therefore, the trailing idler arm casting, shown in Figure 93, was chosen for study. This casting was required to QQ-S-681a Class 4C4 specification. The design was such that the casting required pouring at as low a temperature as possible to limit hot

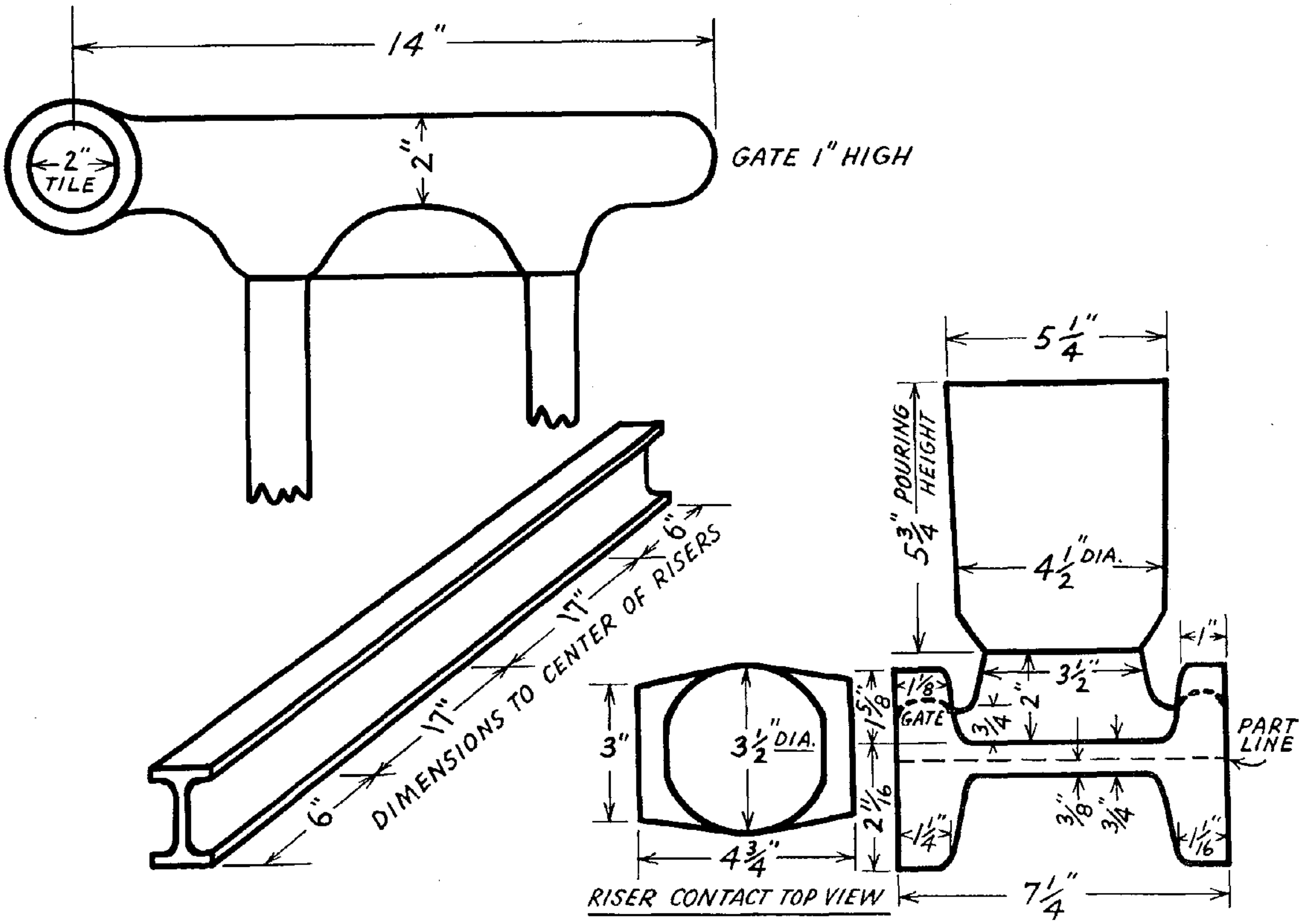


Figure 92—I-beam casting dimensions

tearing. The casting surface after cleaning showed cold shuts and some checks. The chemical composition of the steel is as follows:

	Percent
Carbon	0.24
Manganese	0.85
Nickel	2.45
Chromium	1.27
Molybdenum	0.40
Silicon	0.36
Phosphorus	0.012
Sulfur	0.012

It will be observed from this analysis that the steel was of high hardenability. Furthermore, it had been the experience of the foundry that the casting always cracked on quenching.

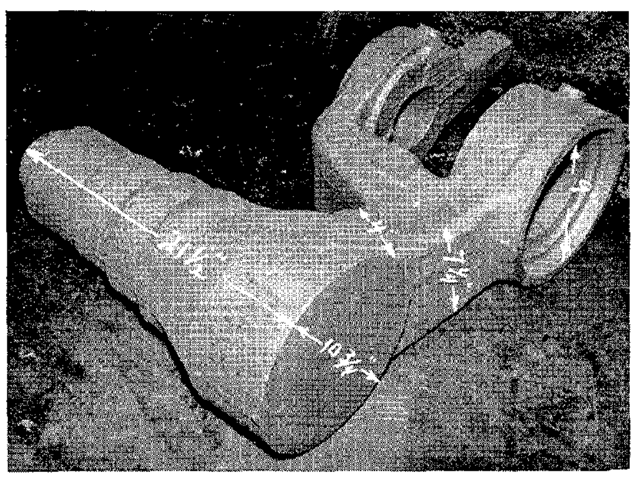


Figure 93—Trailing idler arm casting

The procedure of magnetic particle inspection, blend grinding of all possible indications and fast heating, as given above for the I-beam casting, was followed. The furnace was set at 1750 degrees F. The casting was reexamined after air cooling and again no cracks could be found by thorough 100 percent magnetic particle testing. It also should be pointed out that neither the I-beam casting nor the trailing idler arm was distorted by the heat treatment.

These castings indicated that fast heating rates were not detrimental to the casting.

Armed with this experience, the steel foundry producing the car wheels checked them and it was determined that discontinuities were present in the castings prior to heat treatment.

It is easy to understand why castings do not crack on heat treatment. First of all, the flow of heat through the steel casting is such that large temperature gradients are not established. These temperature gradients could be responsible for stresses to be set up in the casting, especially at the time when the casting surface is contracting upon going through the critical range and the center of the casting is expanding because it is below the critical range.

Such stresses, if they form, do not reach much magnitude because increasing temperature results in stress relief. It is a well-known fact that high stresses in casting are relieved by heating to the temperatures normally employed in tempering, and the higher the temperature employed, the shorter the time for relieving the stresses. Therefore, as the casting temperature rises during the fast heating cycle, the casting stresses present in the as-cast casting are relieved.

TABLE 54

The Effect of Delayed Quenching on the Toughness of Mn-Mo Cast Steel.*

Specimen Size: 1 x 1½ x 5 inches

HEAT TREATMENT: Harden—1600°F 1 hour, water quench
Temper—1050°F 30 minutes

Delay in Minutes Prior to Specimen Entering Quench Minutes	Approximate Temperature of Steel at Time of Quench °F	As-Quenched Hardness BHN	Tempered Hardness BHN	Charpy V-notch Impact at −40°F ft-lbs
0	1600	495	302	54,50
½	1450	477	285	58,55
1	1325	477	285	55,52
2	1200	477	293	48,49
3	1050	477	285	58,56
4	1000	477	285	58,56
5	900	415	277	54,52
6	850	388	273	48,47
7	750	331	269	41,42
8	700	321	262	42,44
9	700	311	255	41,42
10	700	302	248	Stopped
12	650	293	248	Testing
15	550	293	249	

* Courtesy Alex Finlayson, Pacific Car and Foundry Co.

Distortion is more of a problem of casting design and the method of supporting the casting during heat treatment than is the procedure of heat treatment. A slowly heated casting can distort as much as a casting heated at a fast rate.

Effect of Delay in Quenching on the Toughness of Cast Steel

Most heat treating procedures have stressed to a considerable degree the necessity of speedily handling steel castings from the furnace into the quench tank. It is usually pointed out that the time that it takes to perform this operation should be held to the very minimum if an acceptable quenched steel is to be obtained.

The following studies were carried on to determine what effect a delay in quenching would have on the toughness properties of cast steel.

A manganese-molybdenum steel was selected for study because such a steel is not highly hardenable and would reflect considerable change in its quench hardness as time prior to quench was extended. The composition of the cast steel is as follows:

	Percent
Carbon	0.26
Manganese	1.55
Molybdenum	0.50
Silicon	0.36

This steel was produced in bars 1 x 1½ x 5 inches. The bars were heated to 1600 degrees F and quenched in water. A measured time delay of varying periods was permitted. During the period that the casting was out of the furnace, but not in the water, it was held in still air. Hardness values were taken after quenching the steel (¼ inch under the surface) and again after tempering the steel at 1050 degrees F for ½ hour. The toughness of the steel was determined by testing Charpy V-notch impact bars at −40 degrees F. The results of the studies are given in Table 54.

It will be observed that a delay of 5 minutes did not lower the impact value of the steel. As long as an as-quenched hardness value higher than 400 Brinell could be obtained, the steel produced excellent toughness values after tempering. It should be noted that this steel transformed under conditions of fast cooling at a temperature of about 700 degrees F. More highly alloyed steels would transform at a lower temperature.

It should be pointed out, however, that a very light section in a steel of low hardenability, such as a carbon steel, is very sensitive to time and delays in quenching cannot be tolerated. In contrast to this, alloy steels of high hardenability may be quenched after long delays from temperatures in the neighborhood of 800 to 1000 degrees F and produce excellent mechanical properties.

Summary of Fast Heating and Delayed Quenching

1—Steel castings may be heated rapidly to the heat treating temperatures by placing a 70 degree F casting into a furnace at 1750 degrees F without danger of cracking or distorting the castings.

2—Low-alloy castings of high hardenability and large variations in casting thickness can be heated at a fast rate without producing linear discontinuities.

3—Speed in the removal of the castings from the furnace into the quench tank is not critical. Delays upward of several minutes, depending on the steel hardenability, casting mass and rate of cooling, are possible without affecting the toughness of the cast steel.

CONCLUSIONS

The research on the effect of heat treatment variables on the toughness of cast steels was carried on by studying six cast steels of increasing hardenability. These steels were carbon, manganese-boron, nickel-chromium-molybdenum, manganese-chromium-molybdenum, chromium-molybdenum, and manganese-nickel-chromium-molybdenum.

The following conclusions can be drawn from the research:

I—Effect of Quenching Rate

1—The relative severity of the quench results in a variation in the notched-bar impact properties of a steel.

2—Highest impact properties at −40 degrees F are attainable when the as-quenched hardness of a section one inch from the surface is greater than 40 Rockwell C for 0.25 to 0.30 percent carbon content.

II—Effect of Specimen Location in Test Blocks (Keel Castings)

1—A variation of about 33 percent exists between the −40 degrees F Charpy V-notch impact values in any of the quenched and tempered keel test castings. However, there is no fixed pattern for this variation within the keel test casting itself.

2—The horizontally positioned specimens exhibit poorer impact values than the vertical specimens because of their location rather than their direction.

3—The 1¾ x 2¾ inch keel casting apparently produces the highest impact values.

III—Effect of Homogenization Temperature and Time on Toughness

1—Increasing the temperature of homogenization (normalizing) above 1650 to 2050 degrees F does not improve the impact or tensile properties of carbon or low-alloy cast steels.

2—Increasing the time of homogenization (heating time) at any homogenization (normalizing) temperature does not improve the impact or tensile properties of carbon and low-alloy cast steels at any constant hardness level.

3—Section size variations have a slight effect on the impact properties of cast steels; however, variations in section size do not influence toughness properties resulting from changing homogenization temperatures or times.

4—The impact properties of many cast steels are not improved by employing a homogenization (normalizing) treatment prior to quenching. Therefore, this extra heat treatment can be eliminated because both cost and processing time are thereby reduced without lowering casting quality.

5—A short, low temperature homogenizing treatment is advisable for some cast steels that are to be given a quenching treatment if best toughness properties are to be obtained at low temperatures. The reason that some steels apparently require a pretreatment prior to quenching, while others do not, was not resolved by these studies but the reason apparently is associated with steelmaking and not heat treating processes.

IV—Effect of Quenching Temperature and Time on Toughness

1—The heating temperature employed prior to quenching is of no importance regarding its effect on the toughness properties of quenched and tempered cast steel. An advisable temperature is one of 50 to 100 degrees F above the Ac_3 temperature. For most cast steels this would be 1600 to 1650 degrees F.

2—There is no advantage in prolonging the heating time at the selected temperature prior to quenching. A time period of 15 minutes after the casting is heated throughout is ample to secure optimum properties, regardless of the section thickness. A period of 15 minutes at temperature is ample even for commercial heat treating operations.

V—Effect of the Double Quench on Toughness

1—The employment of a double quenching treatment does not improve the toughness or tensile properties of carbon or low-alloy cast steels.

VI—Effect of Tempering Temperature and Time on Toughness

1—Heating quenched steel at any tempering temperature will result in a reduction in the hardness of the steel as the heating time is prolonged.

2—The notched bar impact properties of cast steel increase as the hardness decreases. This condition is a straight line function; however, the rate of increase may or may not be similar and probably will vary from one heat of steel to another. depending on manufacturing conditions.

3—The ductility of the steel improves as the tempering time increases at a specific temperature. The reason for this is that the hardness of the steel is decreasing.

4—Time of heating after the castings reach the tempering temperature can be very short. A period of 15 to 30 minutes is sufficient if the tempering temperature is above 1050 degrees F.

5—The time at tempering temperature is not dependent on the thickness of the section of the casting being tempered.

6—The tempering time and temperature of cast steel can be varied to produce a constant hardness. If this is done there is no drop in hardness nor increase in toughness properties at normal or low temperatures as the tempering time increases.

7—Short time tempering of quenched low-alloy cast steel produces toughness equal to or greater than long tempering times provided hardness values are constant.

8—Changes in section thicknesses from 1 to 6 inches do not adversely affect the use of the short time tempering treatment

VII—The Effect of the Double Tempering Treatment

1—The toughness of cast steels is not improved by a double tempering heat treatment when tempering temperatures are above 1100 degrees F.

VIII—The Toughness of Normalized Cast Steels

1—Single normalizing produces toughness and tensile test properties of the same order as double normalizing (homogenizing followed by normalizing) for 1- and 3-inch sections of carbon and low-alloy cast steels.

2—The effect of different normalizing temperatures and holding times is of very minor importance in securing most acceptable mechanical properties.

IX—Effect of Aging on the Toughness of Cast Steels

1—Some properly heat treated cast steels show an improvement in toughness and ductility by the employment of an aging treatment at 400 degrees F. This treatment may or may not be necessary depending on the steelmaking process. Aging is not necessarily a requirement in high quality, short time heat treatment of steel castings.

X—Effect of Fast Heating and Delayed Quenching on Steel Castings

1—Steel castings may be heated rapidly to the heat treating temperature by placing a 70 degree F steel casting into a furnace at 1750 degrees F without danger of cracking or distorting the casting.

2—Low-alloy castings of high hardenability and large variations in casting thickness can be heated at a fast rate without producing linear discontinuities.

3—Speed is not critical in the removal of the castings from the furnace into the quench tank. Delays upward of several minutes, depending on the steel hardenability, casting mass and rate of cooling, is possible without affecting the toughness of the cast steel.

RECOMMENDATIONS

The research findings and conclusions of the research report permit certain recommendations to be made regarding the future practice of heat treating steel castings so as to produce the best tensile and toughness properties under the most economical conditions and time savings.

The following recommendations apply directly to carbon and low-alloy steel castings.

1—A prior homogenizing (austenitizing or normalizing) heat treatment is not a necessity in obtaining the best mechanical properties. Such treatments should not be employed in the future unless they are employed for other operating purposes, such as: relieving of casting stresses, conditions of welding, chipping or sawing, or to develop scale or otherwise assist in cleaning operations.

2—Short-time heat treatments produce high level strength, ductility and toughness properties. These heat treatments are attained by:

(a) placing castings in furnaces maintained at the normalizing or hardening or tempering temperatures;

(b) place castings on easily transported racks with castings well spaced for heat flow and heat transfer. Do not stack castings on cars;

(c) make temperature studies on all furnaces to ascertain that the furnace is uniformly heated. Install additional burners if necessary. Many furnaces do not have sufficient burners at present;

(d) determine, by the use of thermocouples, the time it takes the center of steel castings of various thicknesses to reach the furnace temperature. Adopt these times but occasionally check;

(e) hold castings at temperature, before air cooling or quenching, a total of from 15 to 30 minutes regardless of casting thickness;

(f) temper castings by placing them in a hot furnace at tempering temperature;

(g) temper castings to a definite hardness value. This can be done by employing high tempering temperatures (1200 to 1300 degrees F) for short periods of total time (15 to 30 minutes).

3—Extra long or multiple heat treatments do not improve mechanical properties. In this regard the following heat treatments are not recommended; double normalizing, double tempering, double quenching, or homogenizing prior to quenching, unless required for reasons other than to obtain satisfactory mechanical properties per se.

4—There is no advantage in employing high heating temperatures prior to air cooling or liquid quenching. It is recommended that temperatures of from 1600 to 1650 degrees F be employed.

5—A few words of caution should be added to the recommendations. Hardness (strength) control is a more exacting operation when short-time tempering cycles are employed. Delays in removing material from the furnace could soften the material so that it is below a specification hardness. Therefore, short time tempering should be set up on a definite schedule basis.

REFERENCES

1. Black, J. E., "Some Aspects of the Charpy Test Applied to Steel Castings." American Foundryman, March, 1952, pp. 56-58.

2. Marcotte, R. J. and Eddy, C. T., "Effect of Homogenization on Cast Steels." Trans. ASM, Vol. 40, 1948, pp. 649-674. Steel Founders' Society Research Report No. 12, May, 1947.

3. Kura, J. G. and Rosenthal, P. C., "Homogenization Heat Treatment for Cast Steel." Trans. AFS Vol. 54, 1946, pp. 154-183.

4. Sims, C. E., Moore G. A. and Williams, G. W. - "The Effect of Hydrogen on the Ductility of Cast Steels." Trans. AIME, Vol. 176, 1948, pp. 283-308.